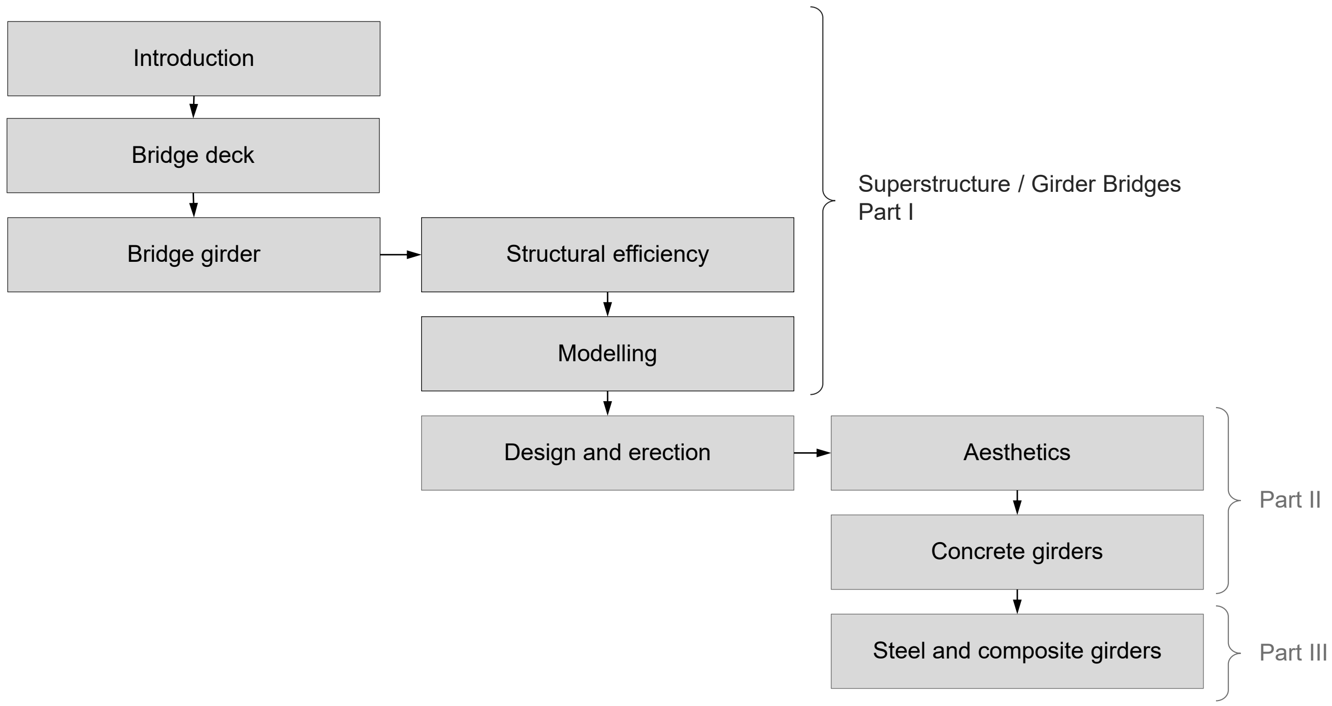
Superstructure / Girder bridges

Design and erection


Introduction
Bridge deck
Bridge girder
Structural efficiency
Modelling
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Superstructure / Girder bridges

Design and erection

Design – Aesthetics

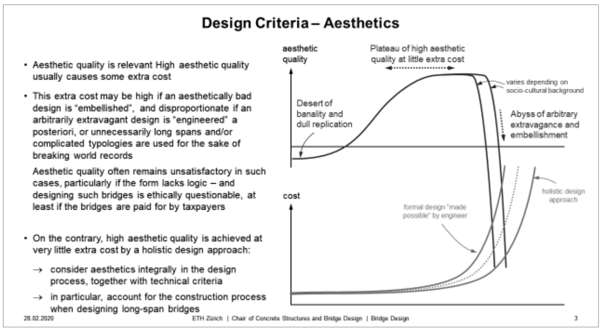
Design – Aesthetics

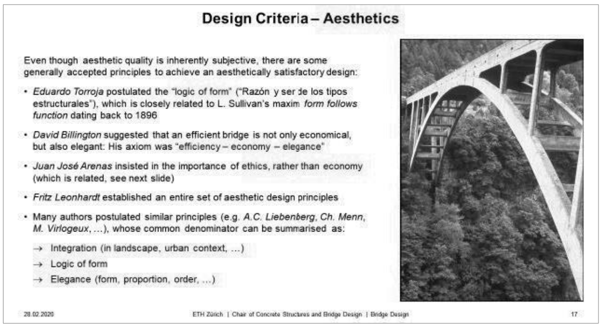
- Aesthetic quality is an important design criterion, see Conceptual Design, Design Criteria – Aesthetics:
  - → Bridge designers are responsible for the aesthetic quality of their bridges, as much as for structural safety and serviceability
  - → Even though aesthetic quality is inherently subjective, there are some generally accepted goals, i.e.

    Integration – Logic of form – Elegance

    and design principles to achieve these goals
- These goals and principles are discussed in this chapter by means of illustrative examples, focusing on girder bridges.
- As this is the first typology (and other typologies also contain bridge girders), some general aspects of bridge aesthetics are also outlined.

- Note: Whether a girder bridge or another typology is appropriate for a specific site is not the question here. Other typologies are discussed in the respective chapters; this then serves as basis for selecting an appropriate bridge typology.





Design – Aesthetics

Aesthetic principles

- Being an object in space, the perception of a bridge is governed by the following elements of visual art
  - → Form (three dimensional, perceived volume)
  - → Contrast (light and shadow, aka “value”)
  - → Colour and visual texture

  and design principles such as:
  - → Balance / proportion
  - → Rhythm
  - → Emphasis
  - → Unity
- These aspects, established in art, architecture and design, are equally relevant to achieve integration, logic of form and elegance when designing bridges.
- Girder bridges (and bridge girders in other typologies) are commonly perceived as elegant if they are transparent and appear slender, and if their span layout is well proportioned → next slides.

Note that the French and German terms «ouvrage d’art» and «Kunstbauten» derive from art. While «ouvrage d’art» directly refers to art («De tels ouvrages sont qualifiés ‘d’art’ parce que leur conception et leur réalisation font intervenir des connaissances où l’expérience joue un rôle aussi important que la théorie. Cet ensemble de connaissances constitue d’ailleurs ce que l’on appelle l’art de l’ingénieur» [Wikipedia]), the German «Kunstbaute» appears to derive indirectly from «Kunst», via « künstlich » («künstliches Bauwerk»).

top Puente de la Barqueta, Sevilla (ES), Juan José Arenas and Marcos Pantaleón (1992). Main span 168 m.

bottom Puente sobre la Ría de Betanzos, La Coruña, ES, Juan José Arenas (1996)

Design – Aesthetics

Colour and visual texture

- The visual texture depends on the material used:
  - → Steel obtains its visual texture through the coating, and the colour can be chosen (with some limitations if MIO coatings are used)
  - → Concrete, weathering steel and timber have their own, characteristic visual texture and colour
  - → Concrete may be coloured by adding pigments to the mix (if done at all, lighter grays are favoured: "white" concrete; other colours are rarely used)

- Concrete surfaces should not be coated, even if the surface is not perfect (e.g. due to improper preparation of casting joints): A coating will look worse

Photos:

Top: Langensandbrücke Luzern, Guscetti-Tournier Ingenieurs with Brauen Wälchli architects (2009), red steel

Bottom: Pont pont sur le Rhône, Rennaz - les Evouettes, Conus&Bignens and Meier+Associés (2012), red concrete

Animated: Regensbergbrücke Zürich

Design – Aesthetics

Transparency

- Bridges are commonly perceived as elegant if they are transparent and appear slender
- Transparency is the opposite of the visual obstruction caused by the bridge as a whole
  → piers (span layout, geometry) decisive
  → girder depth and deck width relevant mainly in low bridges

- Single, narrow piers are much more transparent than wide or twin piers
- Transparency of the piers depends highly on the perspective (direction of sight), particularly for wide piers
- See also Substructure section

Photos:

Top: Puente sobre el río Tajo en el Embalse de Alcantara, LAV Madrid-Extremadura (2016) / Puente en la Variante de Tordesillas (1991), both © CFCSL

Bottom: Viaducto sobre la Presa Mularroya (2016) © IDEAM

Design – Aesthetics

Transparency

- The girder depth is much less relevant in high bridges than in low ones
- The deck width is often more decisive for transparency than the girder depth

Photos:

Top: Viaducto sobre el rio Deba (2015) © IDEAM

Bottom: Viaducto Presa García Sola – Puerto de los Cisneros (2004) © CFCSL

Design – Aesthetics

Transparency

- The girder depth is much less relevant in high bridges than in low ones
- The deck width is often more decisive for transparency than the girder depth

Photos:

Top: Viaducto sobre el rio Deba (2015) © IDEAM

Bottom: Viaducto Presa García Sola – Puerto de los Cisneros (2004) © CFCSL

Design – Aesthetics

Transparency

- The girder depth is much less relevant in high bridges than in low ones
- The deck width is often more decisive for transparency than the girder depth
  … equally in low bridges, unless they are primarily perceived from far away

Photos:

Hardturmviadukt SBB, Zürich, Nänziger Partner (1969), l=1126 m = longest railway viaduct in CH until 2015. Photos © www.brueckenweb.de / Frank Sellke

Photo:

Steinbachviadukt, Sihlsee, dsp (2012). Photo © dsp Ingenieure + Planer

Design – Aesthetics

Transparency

- Truss girders are evidently more transparent than girders with solid webs
- But only when seen from far at the right angle (particularly if they have multiple truss planes)

Viaduc du Viaur, P. Baudin (1902): Cantilevered truss bridge (“Auslegerbrücke”), main span 220 m, acting as three-hinged arch for symmetric traffic load in main span.

Design – Aesthetics

Transparency

- Truss girders are evidently more transparent than girders with solid webs
- But only when seen from far at the right angle (particularly if they have multiple truss planes)

Top: Rheinbrücke Eglisau, Buss&Cie (1897), main span 90 m

Bottom: Thurbrücke Ossingen, Gebrüder Decker (1875), main span 72 m.

Photos © SBB (Eglisau, frontal view) and Georg Aerni (remaining photos)

Design – Aesthetics

Transparency

- Truss girders are evidently more transparent than girders with solid webs
- But only when seen from far at the right angle (particularly if they have multiple truss planes)
- Still, trusses may definitely enhance the aesthetic quality, and if done well, visualise the force flow → logic of form (hard to achieve otherwise in a girder bridge) (see next slide)

Top: Rheinbrücke Eglisau, Buss&Cie (1897), main span 90 m

Bottom: Thurbrücke Ossingen, Gebrüder Decker (1875), main span 72 m.

Photos © SBB (Eglisau, frontal view) and Georg Aerni (remaining photos)

Rheinbrücke Eglisau, Buss&Cie (1897) Photos © SBB

Design – Aesthetics

Transparency

- In conventional prestressed concrete trusses, transparency is limited (large member dimensions for durability reasons)
- Precast concrete segmental bridges with high performance concrete truss webs and external prestressing were promoted by the French contractor Bouygues in the late 1980s. Even if these trusses are indeed transparent (slender members similar to steel), the girder is not.

  → concrete trusses save weight, but in most cases do not substantially enhance transparency

Top: Landquartbrücke Klosters-Serneus, Ingenieurbüro Rigendinger, W. Maag (1993), simply supported curved girder with prestressed concrete trusses, span 76.5 m. Photos © structurae.net /

Bottom: Viaduc de Glacières (overview) and Sylans (animated detail) (1989). Photos © structurae.net / Giacomelli D., Grennerat Y. 1989: “A40 - Les viaducs de Glacières et de Sylans.” *Travaux,* n. 645 (Juli-August), pp. 105-114.

Design – Aesthetics

Apparent slenderness

- The observations regarding transparency of girders also apply to their slenderness
- However, while transparency quite directly depends on the girder's form (or rather shape for a given direction of sight), the apparent slenderness is significantly influenced by
  - proportion (depth, span, height above ground)
  - continuous length of the girder (rather than span) (and rhythm, in case)
  - light and shadow

→ The structural slenderness (ratio height/span) is no reliable measure for the apparent (or visual) slenderness

(which of these bridges has a higher slenderness h/l ?)

Top: Viaducto sobre el rio Deba (2015) © IDEAM

Bottom: Zufahrtsrampen ETH Hönggerberg (1972), Photo © M. Lee

Design – Aesthetics

Apparent slenderness

- The observations regarding transparency of girders also apply to their slenderness
- However, while transparency quite directly depends on the girder's form (or rather shape for a given direction of sight), the apparent slenderness is significantly influenced by
  - proportion (depth, span, height above ground)
  - continuous length of the girder (rather than span) (and rhythm, in case)
  - light and shadow

→ The structural slenderness (ratio height/span) is no reliable measure for the apparent (or visual) slenderness

(although it helps, of course – though this is not a girder bridge, but a cable stayed bridge with an ultra-slender bridge girder)

The following slides show (schematically) different proportions of girder depth, span and height above ground.

Sunnibergbrücke Klosters, Christian Menn / Bänziger Partner AG (1998/2005). Photos © Tiefbauamt Graubünden (top) / Karl Gotsch http://www.karl-gotsch.de/ (bottom)

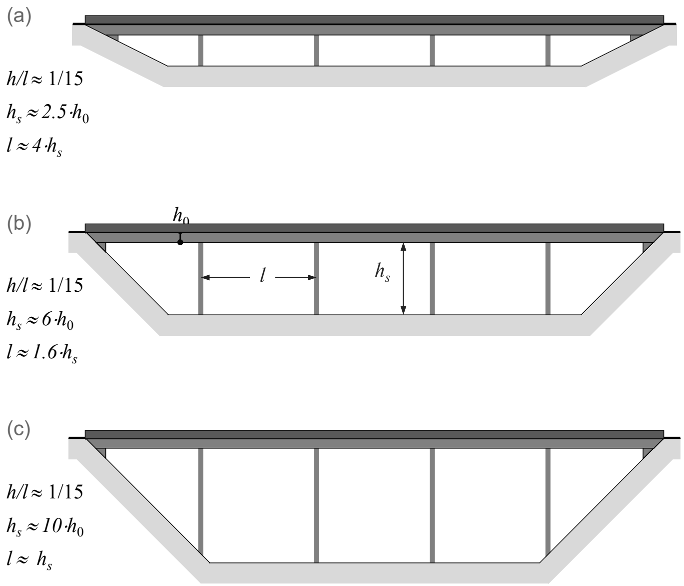
Design – Aesthetics

Apparent slenderness

- Low bridges appear more massive than high bridges, even if they have equal span and slenderness (see figures, example with $h/l \approx 1/15$)

→ Important ratios:
- girder depth / clear height (soffit to ground)
- span / clear height (soffit to ground)

Figures (a)…(c) have
- equal span and depth (= equal structural slenderness h/l)
- variable PGL (= road surface or rails) height above ground
- optional non-structural elements (noise barriers, concrete barriers, …)



Design – Aesthetics

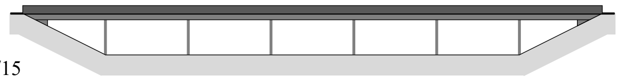
Apparent slenderness

- Low bridges appear more massive than high bridges, even if they have equal span and slenderness (see figures, example with $h/l \approx 1/15$)

→ Important ratios:
- girder depth / clear height (soffit to ground)
- span / clear height (soffit to ground)

Figures (a)…(c) have
- equal PGL height above ground (low height)
- equal structural slenderness h/l
- variable span (and depth since h/l = const.)
- optional non-structural elements (noise barriers, concrete barriers, …)

(a)



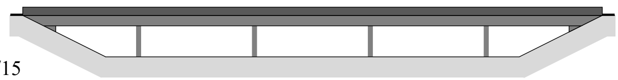
$h/l \approx 1/15$

$h_s \approx 5\ h_0$

$l \approx 2.5\ h_s$

Low bridges: Maximise clear height
→ Choose short spans enabling slender girder

(b)

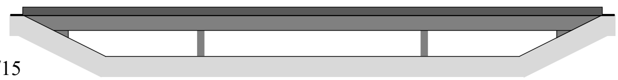


$h/l \approx 1/15$

$h_s \approx 2.5\ h_0$

$l \approx 4\ h_s$

(c)



$h/l \approx 1/15$

$h_s \approx 1.5\ h_0$

$l \approx 9\ h_s$

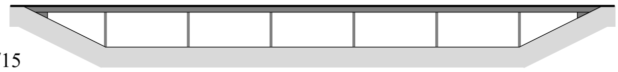
Apparent slenderness

- Low bridges appear more massive than high bridges, even if they have equal span and slenderness (see figures, example with $h/l \approx 1/15$)

→ Important ratios:
- girder depth / clear height (soffit to ground)
- span / clear height (soffit to ground)

Figures (a)…(c) have
- equal PGL height above ground (low height)
- equal structural slenderness h/l
- variable span (and depth since h/l = const.)
- optional non-structural elements (noise barriers, concrete barriers, …)

(a)



$h/l \approx 1/15$

$h_s \approx 5\ h_0$

$l \approx 2.5\ h_s$

Low bridges: Maximise clear height
→ Choose short spans enabling slender girder

Photo: Nudo Norte, Madrid (1973) © CFCSL

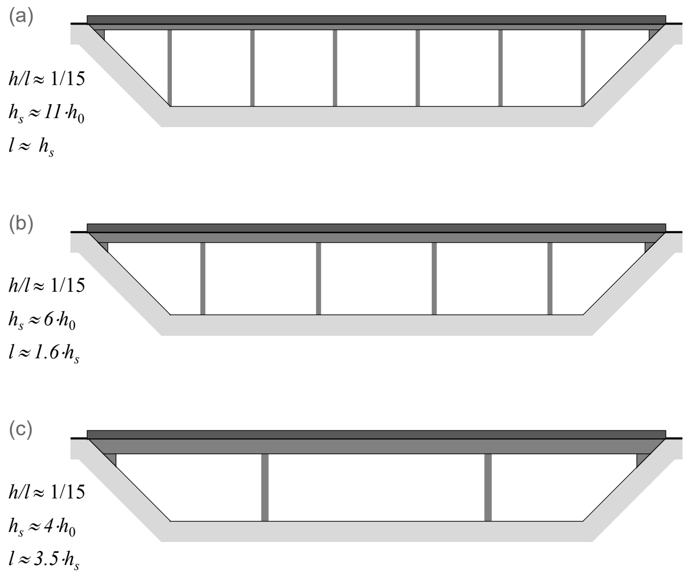
Design – Aesthetics

Apparent slenderness

- Low bridges appear more massive than high bridges, even if they have equal span and slenderness (see figures, example with $h/l \approx 1/15$)

→ Important ratios:
- girder depth / clear height (soffit to ground)
- span / clear height (soffit to ground)

Figures (a)…(c) have
- equal PGL height above ground (medium height)
- equal structural slenderness h/l
- variable span (and depth since h/l = const.)
- optional non-structural elements (noise barriers, concrete barriers, …)



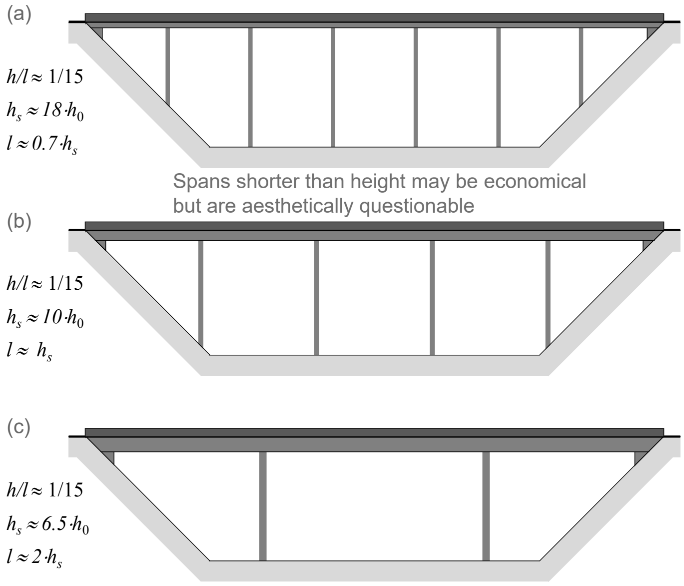
Design – Aesthetics

Apparent slenderness

- Low bridges appear more massive than high bridges, even if they have equal span and slenderness (see figures, example with $h/l \approx 1/15$)

→ Important ratios:
- girder depth / clear height (soffit to ground)
- span / clear height (soffit to ground)

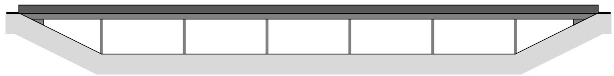
Figures (a)…(c) have
- equal clear height (high bridges)
- equal structural slenderness h/l
- variable span (and depth since h/l = const.)
- optional non-structural elements (noise barriers, concrete barriers, …)

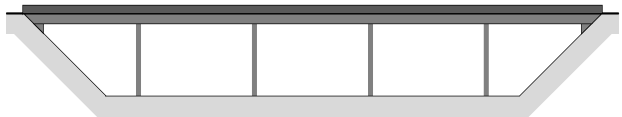


Design – Aesthetics

Apparent slenderness

- As illustrated on the previous slides, non-structural elements (noise barriers, concrete crash barriers, substantially increase the girder depth of slender, short-span bridges, reducing the apparent slenderness





Design – Aesthetics

Apparent slenderness

- As illustrated on the previous slides, non-structural elements (noise barriers, concrete crash barriers, substantially increase the girder depth of slender, short-span bridges, reducing the apparent slenderness
- Full height concrete crash barriers typically extend 1.15 m above the surfacing, corresponding to a total outside visible height of ca. 1.70 m
  → If possible, use steel barriers or lower concrete barrier with additional steel profile (aufgesetzter Leitholm), e.g. 0.85+0.30 m, see below and next slide

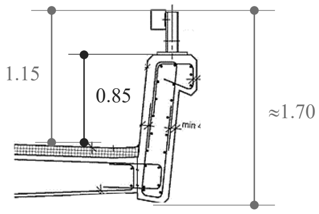


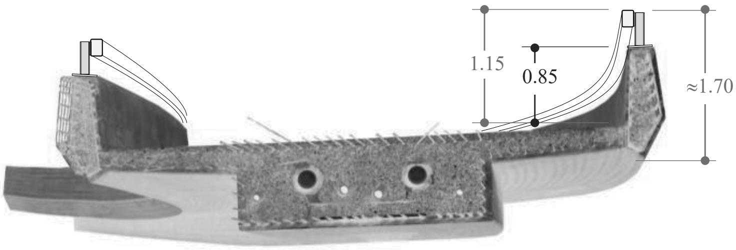
Photo: right side Einfahrtsrampe BW714, Dreieck Zürich West, length 120 m, spans 4x29 m (side span = interior span), dsp Ingenieure + Planer AG, 2004 © W. Kaufmann

bottom:

Design – Aesthetics

Apparent slenderness

- As illustrated on the previous slides, non-structural elements (noise barriers, concrete crash barriers, suicide prevention measures) substantially increase the girder depth of slender, short-span bridges, reducing the apparent slenderness
- Full height concrete crash barriers typically extend 1.15 m above the surfacing, corresponding to a total outside visible height of ca. 1.70 m
  → If possible, use steel barriers or lower concrete barrier with additional steel profile (aufgesetzter Leitholm), e.g. 0.85+0.30 m, see below

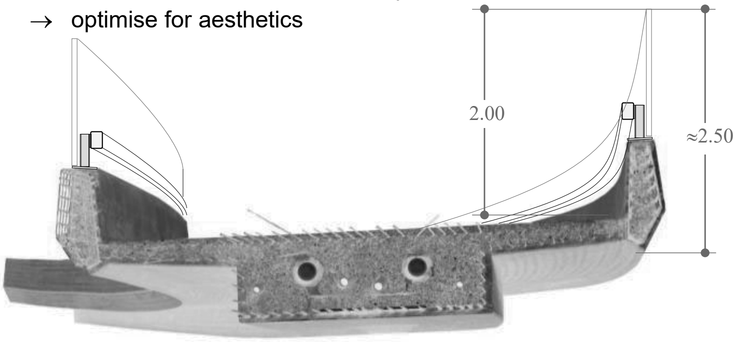


Photos: Zurich Airport, access ramps, dsp (1998-2008). Photos © dsp Ingenieure + Planer

Design – Aesthetics

Apparent slenderness

- Noise barriers are particularly challenging regarding aesthetics, since they are commonly even higher than crash barriers, e.g. 2.00 m above surfacing → visible height of ca. 2.50 m (including parapet)
- «Transparent» noise barriers absorb less noise and require more maintenance (cleaning, vandalism)
  - → often “closed” noise barriers required
  - → optimise for aesthetics



Photos: Kunstbauten Viadukt Wangen (Überführung Mittelgäustrasse), Fürst Laffranchi and dsp (2012). © dsp Ingenieure + Planer

More information see e.g. A. Fürst und M. Laffranchi, Lärmschutz bei Brücken, AGB Bericht 690, 2018.

Design – Aesthetics

Apparent slenderness

- U-shaped cross-sections («Trogquerschnitte») with longitudinal girders serving as barrier enable more slender girders if noise barriers or concrete crash barriers are required
- However:
  - → wide decks require more depth for transverse load transfer (deck is simply supported at its edges)
  - → structural elements above the roadway are problematic regarding impact (railway bridges) and durability (road bridges).
  - → Some owners therefore do not allow this solution (e.g. in CH, such elements are commonly treated as non-structural (though monolithically connected)

Aarebrücke Entlastung West, Solothurn, Fürst Laffranchi (2010). Main span 78 m, built using cantilever method. Photo top © https://mapio.net/place/18112783/, bottom from A. Fürst, M. Laffranchi “Bridges across the Aare River, by-pass West in Solothurn, Betonbau in der Schweiz 2010, Swiss Group of *fib*, pp. 61-65

Design – Aesthetics

Apparent slenderness

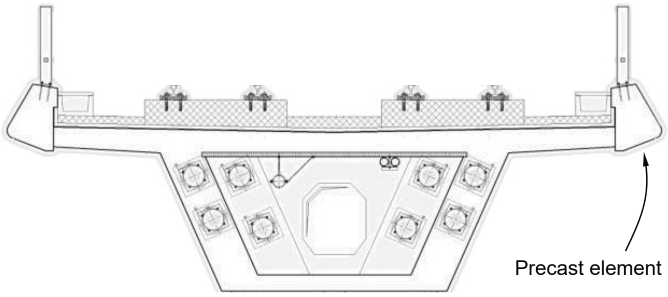
- The apparent slenderness of bridge girders can be significantly enhanced by making use of rhythm and contrast (light and shadow)
- If wide cantilevers are provided, much of the girder depth will be in the shadow, while the parapets / edge beams are much brighter (even on overcast days or at night)
- This contrast greatly enhances the apparent slenderness of bridge girders and allows “hiding” services

Pont du Tiguelet, dsp and Spataro Petoud Partner (2018). Photos © R. Spataro

Design – Aesthetics

Apparent slenderness

- The contrast can be enhanced by inclining the outside of the parapets / edge beams, making them even brighter (use precast edge beams with smooth surface to avoid moss, as in example on this and following slides)
- Note that the example is not a structurally slender bridge ($h \approx 2.00$ m, $h_{tot} \approx 2.60$ m including parapets, typical span $l = 35$ m $\rightarrow h/l \approx 1/17.5$, $h_{tot}/l \approx 1/13.5$), nor are the cantilevers particularly wide



Glattalbahn, Viadukt Glattzentrum, dsp mit Höltschi und Schurter, Beratung Gestaltung Feddersen Klostermann (2009). Photos © dsp Ingenieure + Planer

Design – Aesthetics

Apparent slenderness

- The contrast can be enhanced by inclining the outside of the parapets / edge beams, making them even brighter

Glattalbahn, Viadukt Glattzentrum, dsp mit Höltschi und Schurter, Beratung Gestaltung Feddersen Klostermann (2009). Photos © dsp Ingenieure + Planer

Design – Aesthetics

Rhythm

- The soffit of a girder can be rhythmised using transverse ribs or diagonal struts
- This also enhances contrast → higher apparent slenderness

Top: Viaduc du lac de la Gruyère, Schmidt+Partner (1979), typical span 60.5 m, total length. Photo © La Liberté

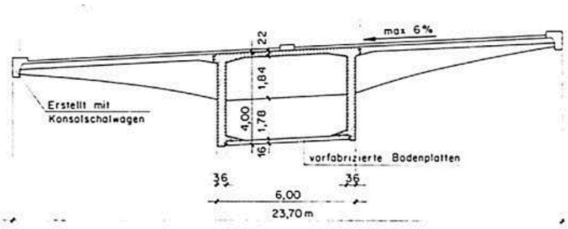
Bottom: Puente sobre la Ría de Betanzos, La Coruña, ES, Juan José Arenas (1996). Photo © Arenas y Asociados

Design – Aesthetics

Rhythm

- The soffit of a girder can be rhythmised using transverse ribs or diagonal struts
- This also enhances contrast → higher apparent slenderness
- And at the same time facilitates
  - → wide cantilevers with moderate weight
  - → efficient construction in stages
    1. cast box girder using a narrow launching gantry
    2. attach precast rib elements to box
    3. cast cantilevers on falsework supported by box girder and precast ribs

→ very efficient method, particularly for wide bridges, used e.g. in several bridges of Swiss motorway network in the late 1970s/early 1980



Viaduc du lac de la Gruyère, Schmidt+Partner (1979), width 23.7 m, typical span 60.5 m, total length 2044 m.

Photos © EPFL iBeton, O. Burdet / figures © BOSSHARD, E. (1981): Das Vorschubgerüst für den viaduc du lac de la Gruyère (Schweiz). In: IABSE Structures, v. 5 (1981).

Design – Aesthetics

Proportion – Span layout

- If the height above ground varies, it may be preferable to vary the spans accordingly

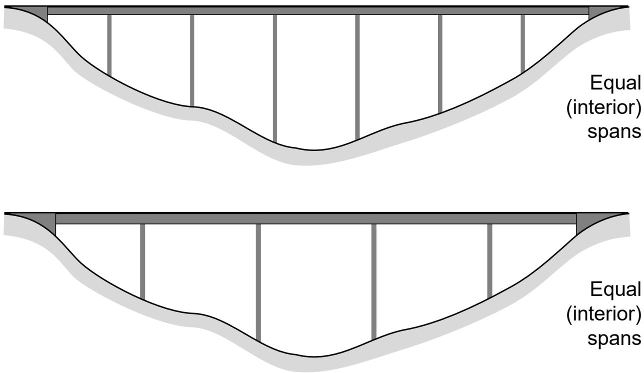


Photo: Viaducto del Istmo (2008). Spans 52+10x66 + 52 m © CFCSL

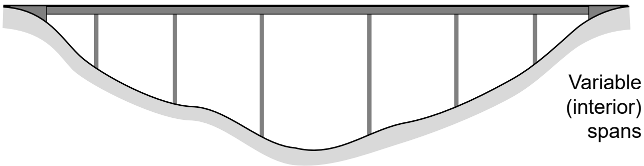
Design – Aesthetics

Proportion – Span layout

- Note however that this is often primarily seen on drawings, but difficult to perceive in reality (unless the bridge can be seen ± in elevation from a far distance), and it breaks the rhythm of equal spans

→ Though postulated as design principle in many textbooks, this must not be given too much weight

→ This also applies to other design paradigms, such as "the number of spans must be uneven", which may be misleading in many cases



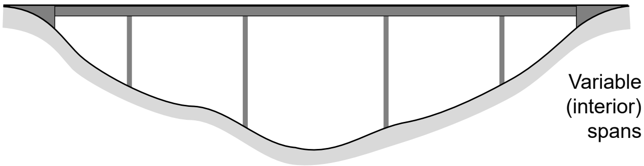
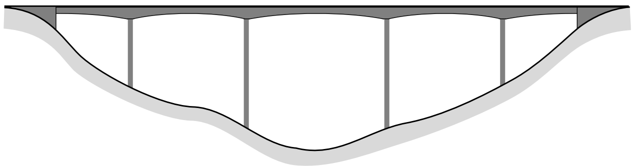


Photo Umfahrung Wattwil, Brücke Thur/SOB, Synaxiy and Gerber Partner (2020). Spans and girder depth increasing from abutments to middle of bridge. © Synaxis

Design – Aesthetics

Proportion – Variable depth

- Variable depth may also be used to achieve more equilibrated proportion and enhance visible slenderness
- However, while often attractive in three-span bridges, variable depth is not necessarily favourable in multispan girders, as the continuity of a constant depth girder is equally attractive
  → use primarily for large spans (structural efficiency)



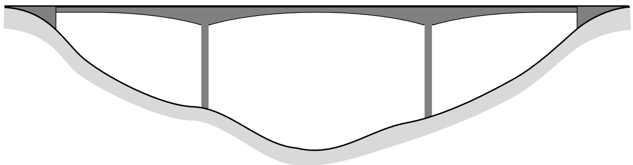
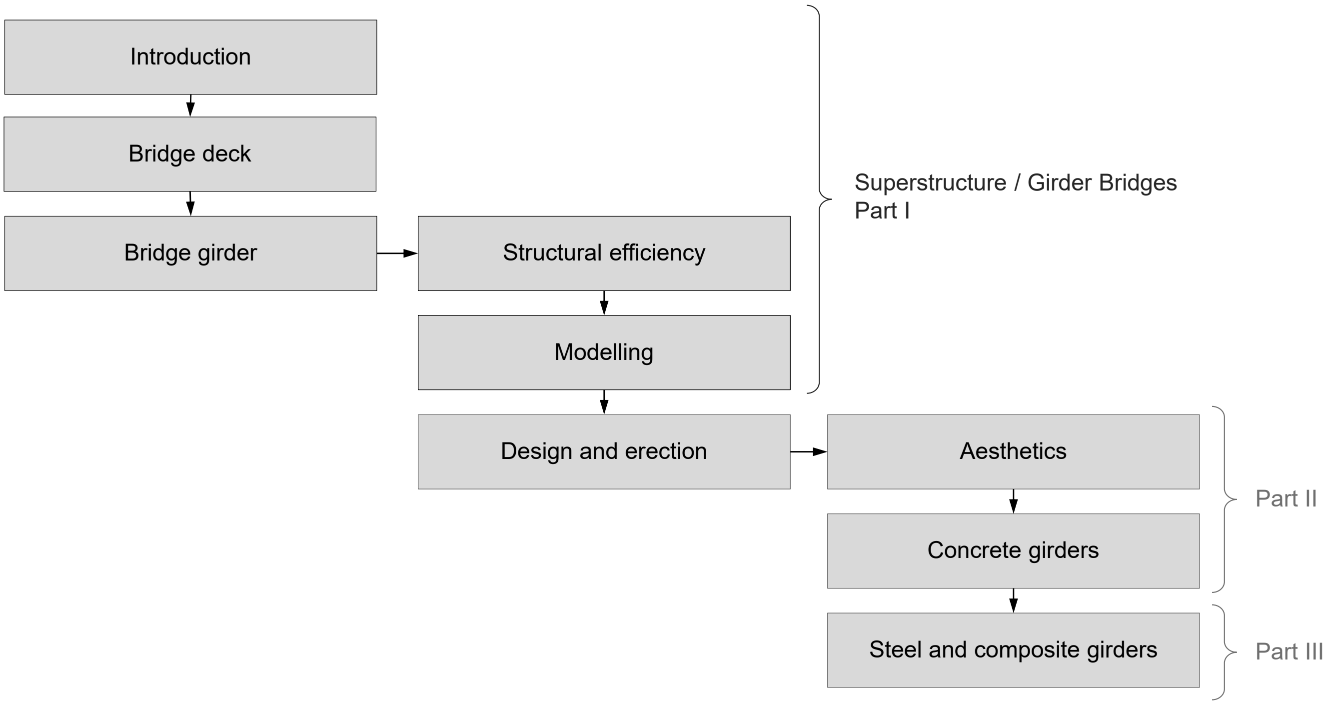


Photo: Viaducto de Montabliz, Cantabria, Spain, Apia XXI (2008). Spans 110+155+175+155+126 m, Maximum pier height 145 m Photo © Ferrovial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Part III

Superstructure / Girder bridges

Design and erection
Concrete girders

Superstructure / Girder bridges

Design and erection
Concrete girders
Bridge specific aspects of structural analysis and design

Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

General remarks

- Some differences compared to building structures
- Spine and grillage models usual
- Usually significant eccentric loads → torsion relevant (see top photo on right side)
- Linear elastic analysis usual, without explicit moment redistribution (redistributions are relied upon, see notes)
- Moving loads → design using envelopes of action effects
- Except for short spans, concrete bridge girders are slender to save weight
  → typically prestressed concrete
  → uncracked behaviour up to decompression
  → consider secondary moments in hyperstatic systems
- Construction is often staged
  → account for staged construction in analysis
- Fatigue is often relevant
  → avoid decompression under fatigue loads

Redistributions of internal stresses are virtually always relied upon, even if temperature gradients and differential settlements are accounted for in the structural analysis: An initially stress-free structure is commonly assumed, but there are always significant internal restraint stresses, e.g. due to hydration heat and differential shrinkage throughout section. This is the reason why concrete tensile stresses must not be accounted for in primary load-carrying mechanisms.

Photos

Top: Eccentric load test with on Almonte Viaduct, Arenas y Asociados (2016). Photo © treneando.com

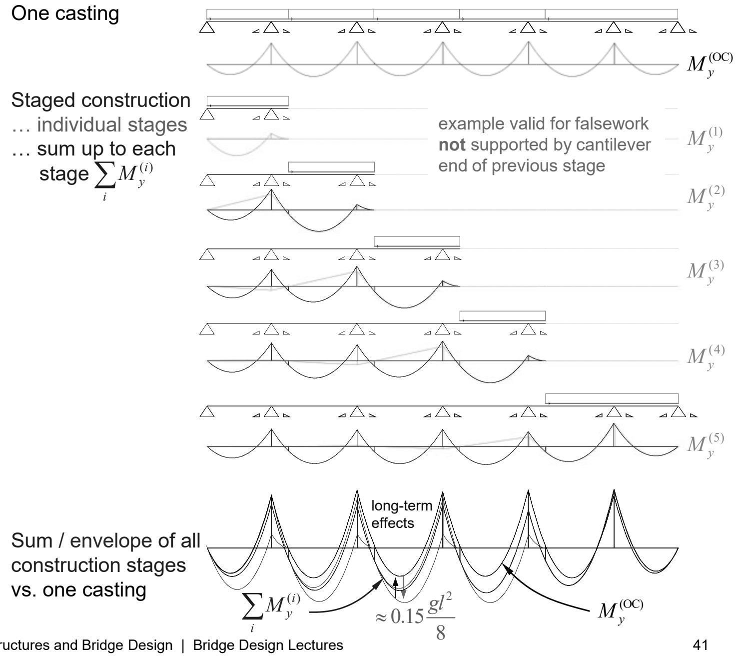
Bottom: Puente sobre el río Narcea, Asturias, Carlos Fernández Casado (2016). © CFCL SL

Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

Staged construction

- Staged construction is usually analysed by linear elastic models where
  → each load is applied in the structural system active at the time of its application
  → action effects due to all loads are added to obtain total action effects
  → significant differences in action effects compared to system cast at once (“one casting” = OC), with strong dependence on construction process (see next slide)
- In ductile girders ($x/d \leq 0.35$, see Stahlbeton I), an analysis of construction stages is not required for ULS design (structural safety)
- Still, analysing construction stages is usually required to
  → design prestressing (decompression?) and check serviceability criteria
  → determine camber (see design/dimensioning)



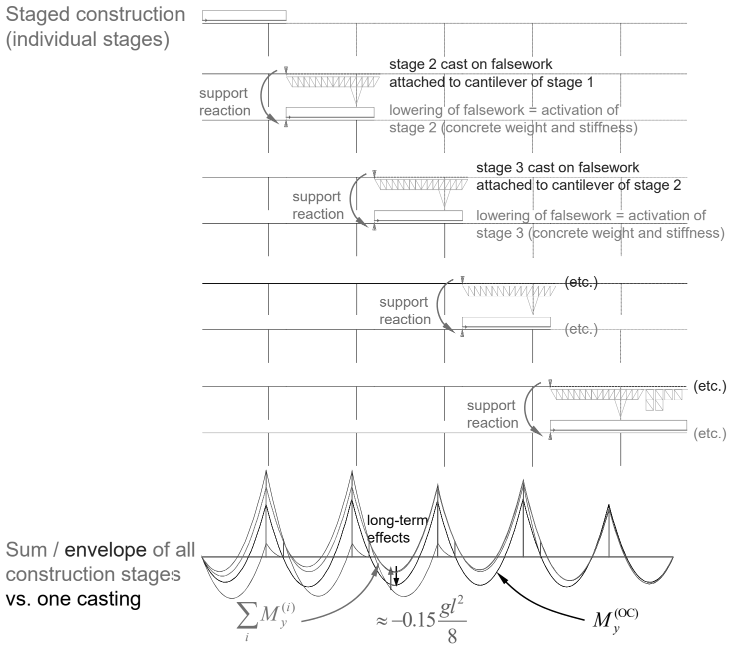
Note that the maximum volume of concrete that can be cast in a single day is in the order of 1’000 cubic meters.

Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

Staged construction

- This slide highlights the strong dependency of action effects obtained from a staged construction analysis on the construction process
  → difference to previous slide: falsework is now supported on the cantilever end of the previous construction stage (this is often done in CH)
  → falsework reaction must be applied to cantilever in casting stage and "removed" (negative load) when the falsework is lowered, i.e. in next stage
  → much larger bending moments over supports than with falsework supported independently
- Due to concrete creep, in either case, the bending moments approach those of the one casting system over time (reaching ≈80% of the latter at $t=\infty$, see Advanced Structural Concrete)
- However, for checking prestressing (e.g. no decompression) at $t=0$, the corresponding bending moments are relevant



Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

Staged construction

- Further to the examples shown on the previous slide, other challenges are frequent in staged construction and need to be accounted for:

  → casting of cross-section in stages (similar to steel-concrete composite girders, see there)

  → temporary supports being added and removed (support reactions must be applied to the system active at removal of supports, see steel and composite girders)

Photos: Innbrücke Vulpera, casting of end span on falsework suspended from cantilevered girder. On request of the contractor, the end span was cast in two stages: (1) U-section, and (2) deck slab, rather than in one casting together as planned. This lead to the problem that the U-section (much stiffer than the falsework on which it was cast) would carry the load of the deck when the latter is cast, but the U-section was not designed for these loads. In order to avoid overloading the U-section, ballast (corresponding to the falsework reaction when casting the deck without U-section in place) was positioned on the cantilever end before casting the U-section, and removed in parallel with casting the deck slab, such that the cantilever tip would not deform while the deck was cast.

Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

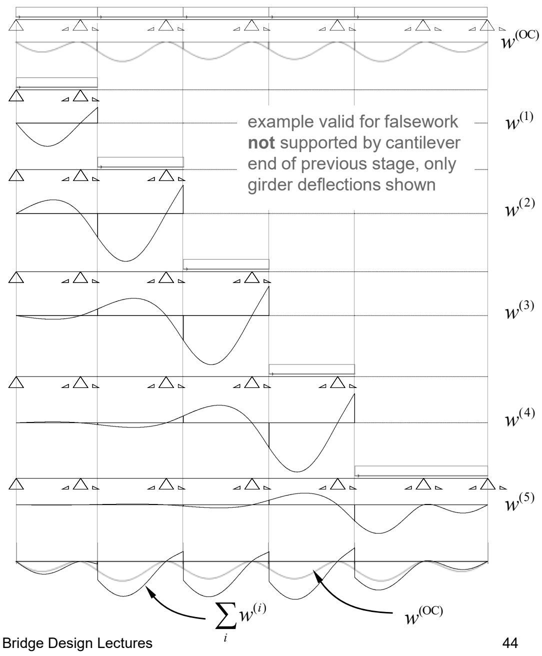
Camber (“Überhöhung”)

- Camber is usually required in bridges. Other than bending moments, deflections do not “creep towards” the one casting system
  → account for prestressing and long-term effects
  → account for staged construction
- There is no «safe side» in determining camber
  → do not provide more camber than required
  → avoid construction processes requiring large or complex camber (e.g. twisting of curved girders) where possible
  → adopt conceptual measures to accommodate deviations from expected deflections, particularly to conceal kinks between stages which may extremely harm appearance (e.g. cast parapets (Konsolköpfe) at a later construction stage, as usual in in CH)

One casting (use for long-term girder deflection)

Staged construction (short-term deflection of individual stages)

Sum of construction stages vs. one casting



Concrete girders – Structural analysis and design

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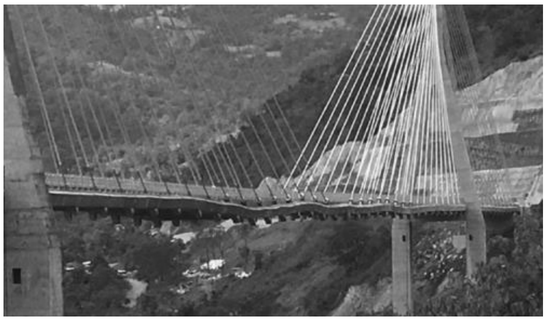


Hisgaura bridge, Colombia

Photo: top: http://oronoticias.tv/ ; bottom: https://caracol.com.co/

Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

Camber ("Überhöhung")

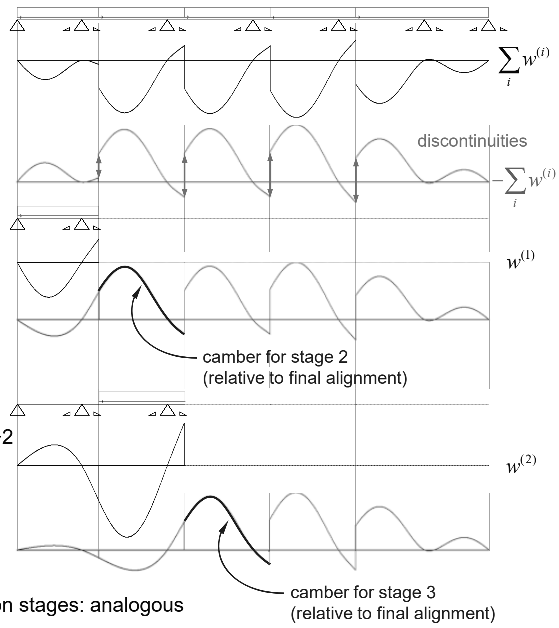
- The camber corresponds to the sum (with opposite sign) of the expected displacements due to
  … deformations of the formwork+falsework
  (not shown in the slides, including removal of temporary supports)
  … deformations of the girder (short+long term)
  (short-term contribution shown in slides)
- The camber in the example is discontinuous (vertical offset) at all construction joints, since each element only exists + deforms after it has been cast
- This is usual unless construction joints are located over piers, since the camber corresponds to the (negative) difference between the position before casting and the final alignment
- Considering the deflections of the stages cast before reaching a construction joint, the camber of adjacent stages is continuous

Girder deflection due to staged construction

Camber due to staged construction (girder part only, negative of above)

+ deflection stage 1
→ deflection incl. camber after casting stage 1

+ deflection stage 1+2
→ deflection incl. camber after casting stage 2



… further construction stages: analogous

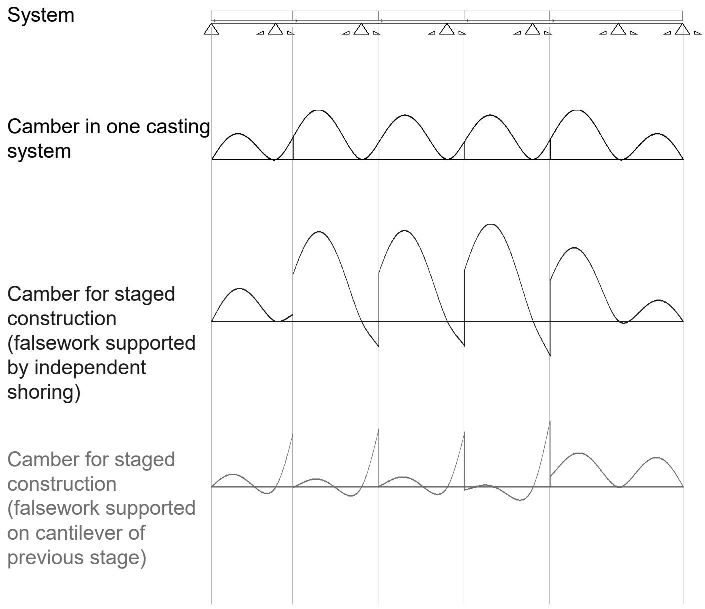
How camber is realised depends on the erection method, particularly on the type of falsework used. As an example, if simply supported falsework girders are used, they have to be individually cambered for their individual deflection (under wet concrete load at casting), plus the height of the girder camber curve's segment between the falsework girder supports. The latter of course need to be set at the level of the camber curve (plus any anticipated settlement of falsework supports).

Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

Camber ("Überhöhung")

- The deflections resulting from the staged construction, hence the camber, differ significantly from those in the one casting system
- As for the bending moments (or even more pronouncedly), they depend strongly on the construction process, as highlighted in the figure by comparing the camber for the two cases illustrated already for the bending moments:
  … falsework supported by independent shoring
  … falsework supported on the cantilever end of the previous construction stage



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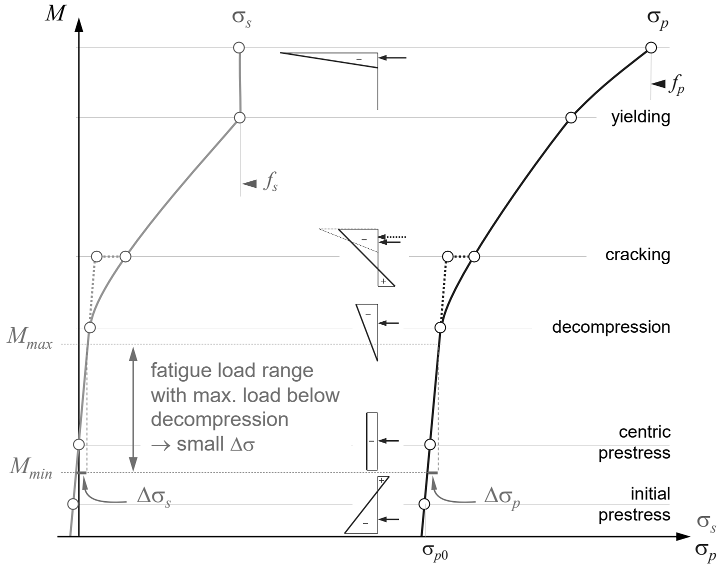
Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

Fatigue

- Fatigue is often relevant, particularly
  → in bridge decks
  → railway bridges
- As illustrated on the right, stress variations in reinforcement and prestressing are much more pronounced after decompression of the cross-section
  → select prestressing level in fatigue-relevant structures such that no decompression occurs under fatigue loads



Concrete girders – Structural analysis and design

Bridge-specific aspects of analysis and design

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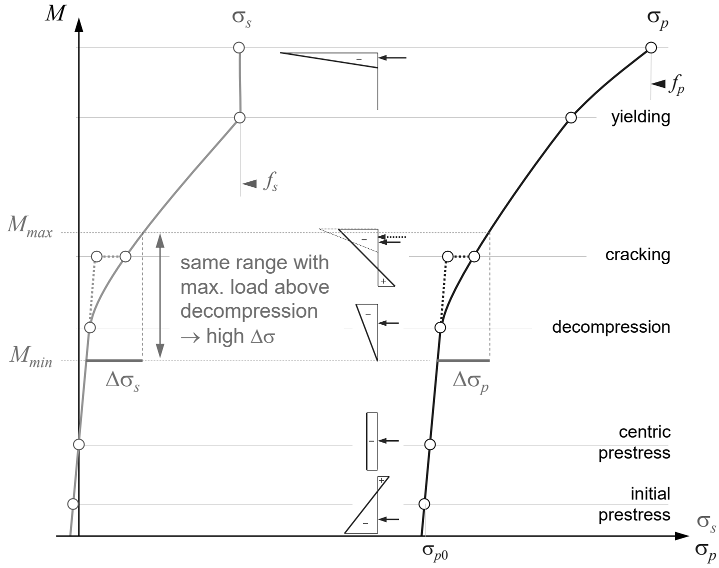


Superstructure / Girder bridges

Design and erection

Concrete girders

Typical cross-sections and details

Concrete girders – Typical cross-sections and details

Typical cross-sections

- Solid cross-section
- Box cross-section
- Multicellular cross-section
- Open cross-section

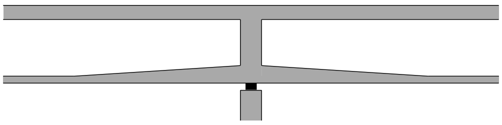
Slab geometry

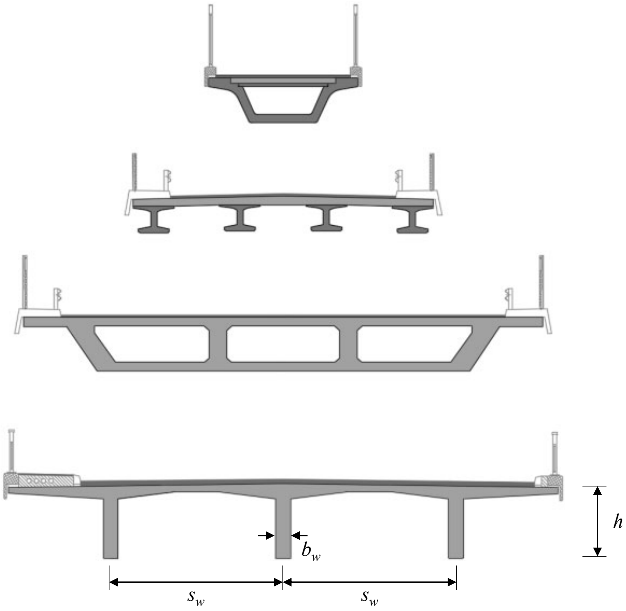
The deck slab and the bottom slab in box girders contribute significantly to the dead load

→ variable depth = haunches often provided to save weight, in spite of the more complicated formwork:

… transversely to increase the transverse bending and shear resistance of deck and bottom slab (in box girders)

… longitudinally to obtain a thicker compression flange (usually only bottom slab, see notes):





Usually, in the longitudinal direction only the bottom slab is provided with variable thickness for the following reasons:

- the deck slab is wider and usually a higher minimum thickness → much larger area than bottom slab
- the hogging bending moments over the piers (bottom flange acting in compression) are usually much higher than the sagging moments in the spoan
- a lontitudinally varying thickness of the deck would complicate the construction process much more (bottom slab is usually cast without top formwork, or only narrow strips along webs)

The thicker bottom flange is favourable for the bending resistance, but more often required to increase the rotation capacity (lower x/d).

Concrete girders – Typical cross-sections and details

Number of webs / girders

The primary criterion for the selection of the number of webs is the weight of the cross-section.

In low-moderate depth girders, the deck (and bottom slab in box girders) constitute most of the dead load:

→ select number of webs and respective spacings s_w such that thin slabs are possible (with haunches, see previous slide)

In deep girders, the webs significantly contribute to the dead load (and are statically inefficient, see notes):

→ reduce web thickness b_w to minimum required for casting (space for tendons and vibrating needle!)

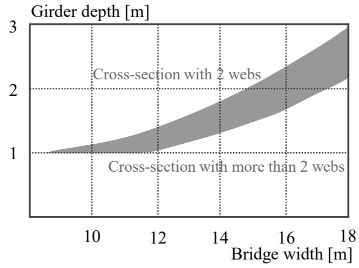
→ reduce number of webs by providing transverse ribs (however: complicated formwork)

→ use transverse prestressing

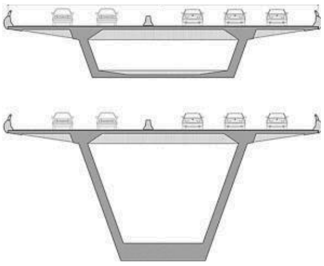
→ reduce web weight (truss webs) in long-span bridges

The figure on the right indicates that, as outlined above, more than two webs are (if at all) appropriate in girders with low-moderate depth only, except in very wide bridges.

Usual number of webs [Menn 1990] as a function of girder depth and bridge width …



... but wider bridges are built with 2 webs (e.g. in Montabliz: deck width 26.10 m):



Viaducto de Montabliz, ES, 2008, Apia XXI

Illustration: Ch. Menn, Prestressed Concrete Bridges, 1990.

Viaducto de Montabliz, Cantabria, Spain, 2008, Apia XXI Ingenieros, Photo © Ferrovial Agroman

Concrete girders – Typical cross-sections and details

Number of webs / girders

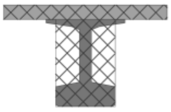
Transverse ribs or struts not only enable reducing the number of webs in wide girders.

They are also aesthetically relevant, since they rhythmise the girder – which is often favourable in long, otherwise monotonic or massive bridges.

Puente sobre la Ría de Betanzos, La Coruña, ES, Juan José Arenas (1996)

Concrete girders – Typical cross-sections and details

Cast-in-place girders



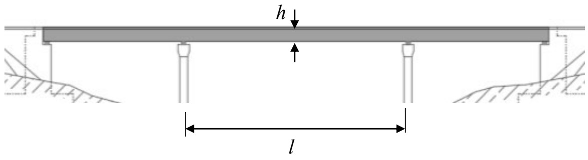
- Simple cross-sectional geometry = formwork and construction is more important than optimising weight. Hence, they are usually

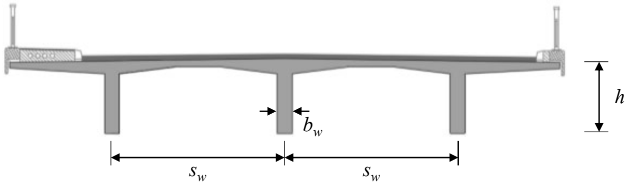
→ heavier than precast girders

→ s_w is larger than in precast girders (less webs / beams ⇨ simpler construction)

- Variable depth is easier to achieve than in precast girders. Still, for small and medium span bridges, constant depth is favoured due to the simpler construction (formwork, falsework)

- Cast-in-place girders are usually continuous over the piers for structural efficiency





Concrete girders – Typical cross-sections and details

Cast-in-place girders

- Typical / economical slenderness of continuous girder bridges:

constant depth girder

$$\frac{1}{22} \le \frac{h}{l} \le \frac{1}{17}$$ 

$$\frac{1}{18} \le \frac{h}{l} \le \frac{1}{15}$$ 

variable depth girder

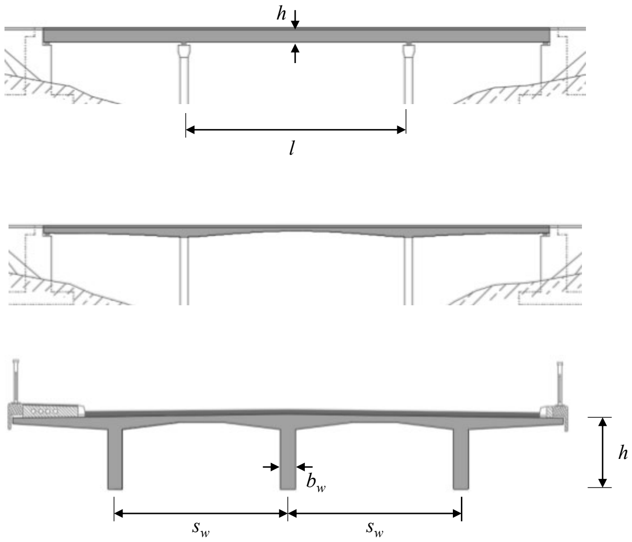
supports $\frac{h}{l} \cong \frac{1}{20}$ 

midspan $\frac{h}{l} \cong \frac{1}{45}$ 

free cantilevered

supports $\frac{h}{l} \cong \frac{1}{17}$ 

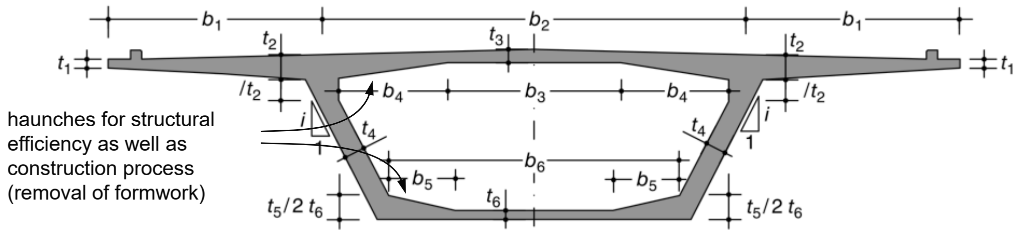
midspan $\frac{h}{l} \cong \frac{1}{50}$ 



Concrete girders – Typical cross-sections and details

Cast-in-place girders

- Typical geometry and minimum thicknesses for pre-dimensioning of a box girder



deck span ratios	$b_1/b_2 \approx 0.45$; $b_4/b_2 \approx 0.2$; $b_5/b_6 \approx 0.2$
deck slenderness	$b_3/t_3 \leq 25\ldots30$; $b_6/t_6 \leq 30$;
minimum thicknesses	$t_1 \geq 0.26$ m (for cast-in-place parapet = CH; for prefabricated edge beams 0.20 m is sufficient) $t_2 \geq 0.35$ m (resp. 0.40…0.45 m if full tandem axle acts on cantilever, i.e. if $b_1 >$ ca. 2.5 m) $t_3 \geq 0.25$ m $t_4 = b_w \geq 0.35$ m $+ n_p \cdot 0.1$ m ($n_p \leq 2$ = number of interior prestressing tendons next to each other in web) $t_6 \geq 0.20$ m (resp. 0.26 m if prestressing tendons are running in bottom slab)
web inclination	$i \geq 3\ldots4\ \ldots5$ (flat webs are structurally inefficient and complicate the reinforcement layout at slab connections)

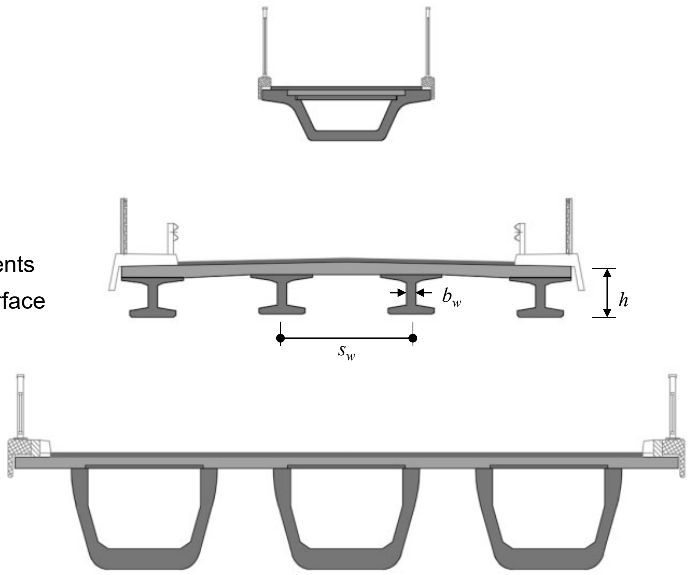
For the preliminary design of box girder sections, one may adopt the following relationships from the design, according to notations of the slide.

Source and illustration: Adapted from Reis Oliveiras, Bridge Design.

Concrete girders – Typical cross-sections and details

Precast girders

- Complex cross-section geometries and structural optimisation possible (maximise radius of gyration $\sqrt{\frac{I}{A}}$)
- Construction / erection = positive
  - simple construction
  - fast erection
  - elimination of falsework
- Durability / maintenance = negative
  - thin cross-section components
  - large exposed concrete surface
  - many construction joints
- Precast girders are often simply supported (continuity over supports complicates construction and slows down erection speed)
- Maximum spans l and slenderness h / l depend on the erection method

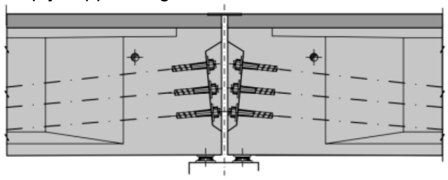


Concrete girders – Typical cross-sections and details

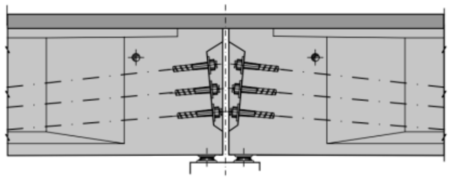
Precast girders – Arrangement over supports

- Different possible schemes for precast girder bridges, regarding the support region, are illustrated on the right
- These are illustrated in more detail on the next slides
- Erection procedures see separate subsection

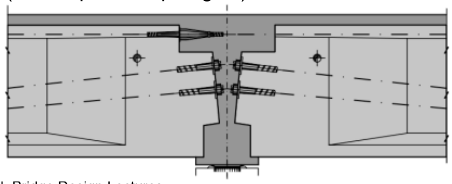
Independent, simply supported girders



Partial continuity (monolithic deck slab)



Full continuity (cast-in-place diaphragms)



Illustrations adapted from Reis Oliveiras, Bridge Design.

Concrete girders – Typical cross-sections and details

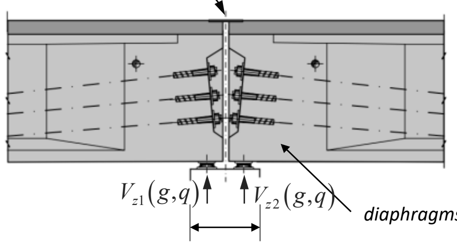
Precast girders – Arrangement over supports

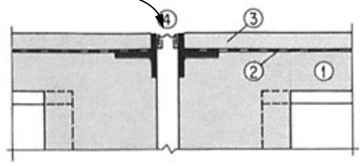
Independent, simply supported girders

- Erection of simply supported girders without establishing continuity
- Deck slab may be partially precast or fully cast in situ after erection (but not monolithic over supports!)
- Pier cap must be wide enough to locate the permanent supports of both girders
- Requires bridge expansion joint at each support

  → avoid in road bridges since expansion joints:
  … may cause severe damage if leaking
  … require maintenance even if properly detailed to avoid leakage, which is difficult, see notes)
  … are expensive but have a short service life
  … affect user comfort and cause noise

  (see support and articulation chapter for details)





1. *Cast-in-place deck slab*
2. *Waterproofing membrane*
3. *Wearing surface*
4. *Expansion joint*

Note that properly detailing expansion joints over piers to avoid durability problems is much more difficult than at an abutment. In particular, access to the expansion joint from below (for maintenance and inspection, i.e., to detect leakage early) is usually not feasible.

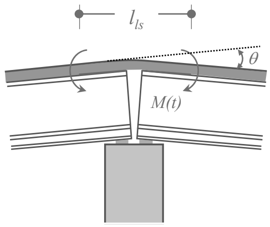
Illustrations: Reis Oliveiras, Bridge Design (top); Ch. Menn, Prestressed Concrete Bridges (bottom)

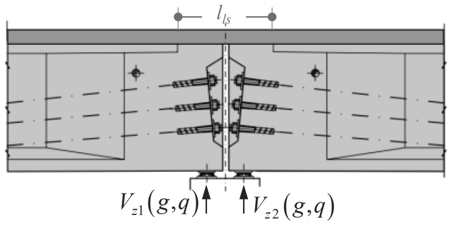
Concrete girders – Typical cross-sections and details

Precast girders – Arrangement over supports

Partial continuity (monolithic deck slab)

- Erection of simply supported girders
- Pier cap must be wide enough to locate the permanent supports of both girders
- Establishment of partial continuity through the cast-in-place deck → no expansion joints, but weak section (only slab transfers M_y at supports)
- If the deck is precast, only the part over the support ("link slab") is cast in place
- The slab is horizontally disconnected from the girders over the length l_{ls}
  - → allow relative horizontal displacements between link slab and girders (e.g. via elastomeric pads, see figure)
  - → M_y over supports depends on the relative rotation θ_y of the two girder ends (which define the curvature χ_y of the slab)

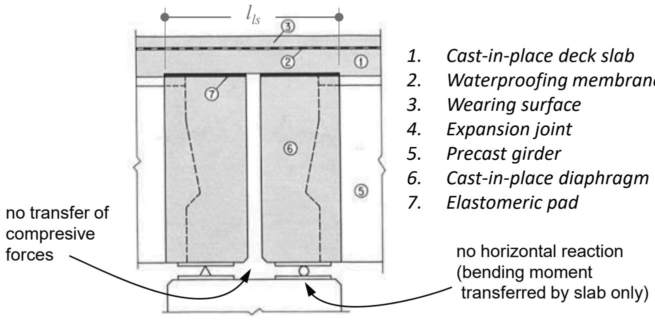




typical length l_{ls} of «link slabs»:

$15\ \text{m} \leq l \leq 20\ \text{m} \rightarrow 1\ \text{m} \leq l_{ls} \leq 2\ \text{m}$

$30\ \text{m} \leq l \leq 40\ \text{m} \rightarrow 2\ \text{m} \leq l_{ls} \leq 4\ \text{m}$



1. *Cast-in-place deck slab*
2. *Waterproofing membrane*
3. *Wearing surface*
4. *Expansion joint*
5. *Precast girder*
6. *Cast-in-place diaphragm*
7. *Elastomeric pad*

Note that the rotation over the support corresponds to the elongation of the link slab, that can be calculated using e.g. the tension chord model, divided by the lever arm of internal forces *z*.

Theoretically, it would be possible to avoid the weak section (transfer significant bending moments, rather than just those in the deck slab) by closing the joint between the girders at the bottom flange level; however, this would require a massive reinforcement in the top slab since bending moments would more or less correspond to those of a fully continuous girder. If full continuity is required for stiffness or strength), the solution illustrated on the following slide is therefore preferred.

Illustrations: Javier Manterola, Puentes I (top left); Reis Oliveiras, Bridge Design (top right); Ch. Menn, Prestressed Concrete Bridges (bottom)

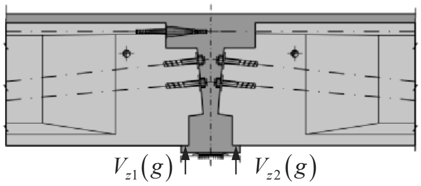
Concrete girders – Typical cross-sections and details

Precast girders – Arrangement over supports

Full continuity (cast-in-place diaphragms)

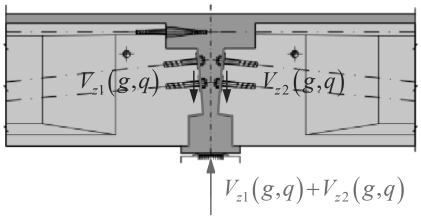
- Erection of simply supported girders
- Pier cap (ev. with auxiliary falsework) must accommodate the temporary supports of both girders as well as the common final support
- Establishment of full continuity through
  … cast-in-place diaphragm and deck
  … continuous prestressing
  → no expansion joints, no weak section
- Vertical shear forces from the two spans $V_{z1,2}$ must be transferred to the support reaction $V_{z1}+V_{z2}$ through the interface between concrete cast at different times (shear keys often required)
- Post-tensioning is (partly) continuous over supports
  → many solutions (see lecture of M. Meyer)
  → careful detailing essential
- Account for long-term effects (moment redistribution from $t=0$ to $t=\infty$)

Erection of simply supported girders

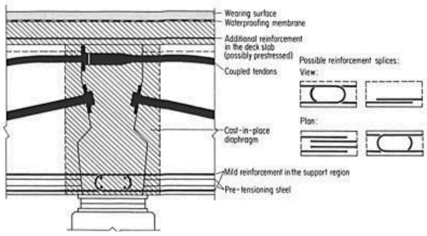


Casting of Diaphragms

Prestressing for continuity



Careful detailing of waterproofing and bottom reinforcement



Illustrations: Reis Oliveiras, Bridge Design (top); Ch. Menn, Prestressed Concrete Bridges (bottom)

Superstructure / Girder bridges

Design and erection
Concrete girders
Prestressing concept

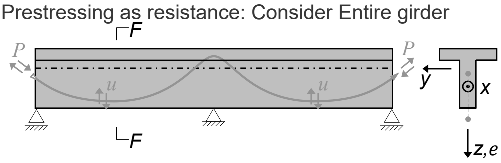
Concrete girders – Prestressing concept

Prestressing concept

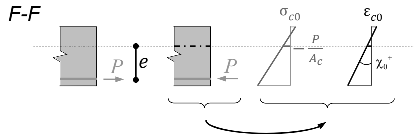
The prestressing concept contains (see Stahlbeton II):
- degree of prestress
- tendon layout (profile, anchorages, …)
- tendon sizing
- stressing sequence (where, when)

The students are assumed to be familiar with prestressed concrete and the two options for treating prestressing in structural analysis:
- "prestressing as resistance"
  … consider entire system
  … prestressing causes residual stress state in cross-sections
  … in statically indeterminate systems, corresponding deformations are not compatible with the supports, causing, restraint actions («secondary moments») = action effects in the entire system
- "prestressing as load"
  … consider partial system = girder without tendon
  … anchor, deviation + friction forces are acting on this subsystem

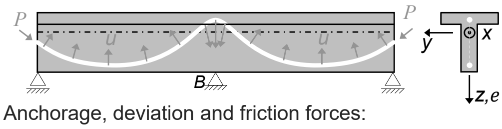
Prestressing as resistance: Consider Entire girder



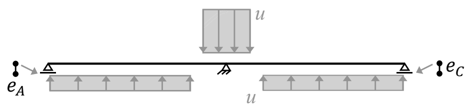
Residual stress state (illustrated at midspan)



Prestressing as load: Girder without tendon



Anchorage, deviation and friction forces:



Concrete girders – Prestressing concept

Degree of prestressing

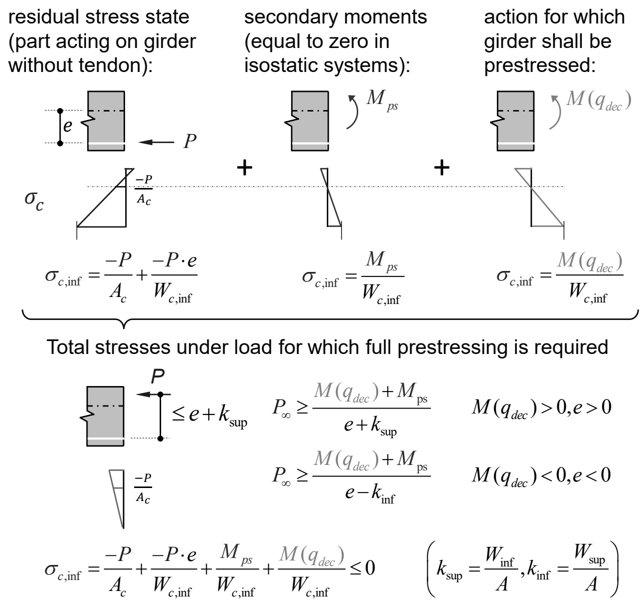
The students are also assumed to be familiar with the concept of the degree of prestressing (Vorspanngrad).

When defining the degree of prestressing (see Stahlbeton II), the load q_{dec} that causes decompression is referred to.

The required prestressing force is obtained as illustrated in the figure (derivation of formula for negative bending moments accordingly).

In concrete bridges, a full prestressing for the following loads is common:

- Road bridges (typically, $P/A_c \approx 3 \ldots 5$ MPa):
  → permanent load (usual in CH)
  → permanent load + frequent load (usual e.g. in F)
  → permanent load, but decompression allowed in span (less durable, avoid)
- Railway bridges (typically, $P/A_c \approx 4 \ldots 7$ MPa):
  → permanent load + fatigue load (usual)
  → permanent load + frequent load (higher durability)



Often, rather than strictly requiring a full prestressing for the specified load (i.e., no decompression in the extreme fibre), a nominal tensile stress in the order of magnitude of the tensile strength of the concrete is admitted, particularly if full prestressing for loads exceeding the permanent load is required. If only a full prestressing for permanent loads is required, and no restraints (temperature difference, differential settlements) are accounted for when checking decompression, admitting such a nominal tensile stress may affect durability.

Note that for fatigue checks, a cracked elastic analysis is required in such cases, even if a „full" prestressing for permanent load and fatigue load was specified (since the section may crack due to the admitted nominal tensile stress).

Alternatively, rather than requiring no decompression at thecross-section edged, decompression at the level of prestressing tendons may be required.

Concrete girders – Prestressing concept

Degree of prestress

In highly prestressed girders (e.g. railway bridges), decompression may occur under permanent load and prestressing, on the side of the cross-section opposite to the tendons. This is often tolerable in construction stages (reduced dead load q_0), but should usually be avoided in service (full permanent load). In checking this condition, the initial prestressing force must be used (*P* is unfavourable in this case), see illustration.

Prestressing hardly ever acts on its own. Rather, a significant portion of the girder's self-weight is usually activated at the very moment of applying the prestressing forces (that tend to lift the girder off the formwork)

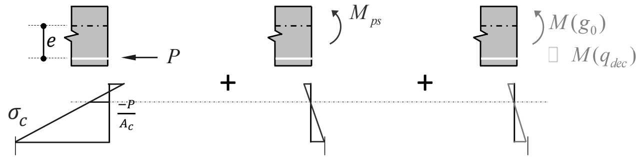
→ the case «prestressing only» need not to be checked for decompression usually

→ strictly speaking, this should be accounted for when determining the strain difference $\Delta\varepsilon$ between girder and tendon (frozen when grouting) – but usually, concrete strains are completely neglected in determining $\Delta\varepsilon$ (see Stahlbeton II)

residual stress state (part acting on girder without tendon):

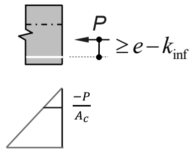
secondary moments (equal to zero in isostatic systems):

action for which girder shall be prestressed:



$$\sigma_{c,\sup} = \frac{-P}{A_c} - \frac{-P\cdot e}{W_{c,\sup}} \qquad \sigma_{c,\sup} = \frac{-M_{ps}}{W_{c,\sup}} \qquad \sigma_{c,\inf} = \frac{-M(g_0)}{W_{c,\sup}}$$

Total stresses without variable load



$$P_0 \le \frac{M(g_0)+M_{ps}}{e-k_{\inf}} \qquad M(g_0)>0, e>0$$

$$P_0 \le \frac{M(g_0)+M_{ps}}{e+k_{\sup}} \qquad M(g_0)<0, e<0$$

$$\sigma_{c,\sup} = \frac{-P}{A_c} - \frac{-P\cdot e}{W_{c,\sup}} + \frac{-M_{ps}}{W_{c,\sup}} + \frac{-M(g_0)}{W_{c,\sup}} \le 0 \qquad \left(k_{\sup} = \frac{W_{\inf}}{A}, k_{\inf} = \frac{W_{\sup}}{A}\right)$$

Concrete girders – Prestressing concept

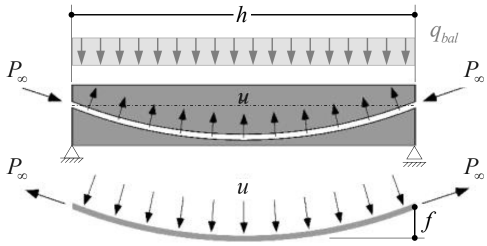
Degree of prestress

The formulas for determining the prestressing force P on the previous slide contain the secondary moment M_{ps}, which in turn is a function of P and the tendon layout. Hence, an iterative procedure is required to determine P.

A first estimate of the required prestressing force may be obtained by the load balancing method:

- choose prestressing layout and force such that deviation forces *u* correspond to a certain load q_b
  → pure axial compression under load $q_{bal} = u$
  (if anchor forces act in centroid of cross-section)
- full load balancing is hardly ever required
- in order to achieve full prestressing for q_{bal} (i.e., no decompression under this load), deviation forces of about $u \approx 0.8\ q_{bal}$ are typically sufficient
- The interpretation of prestressing as load is particularly useful for unbonded prestressing (including ungrouted tendons in construction stages)

Deviation forces fully compensating load q_{bal}



$$u = 8\frac{P_\infty f}{l^2} \geq q_{bal} \rightarrow P_\infty \geq \frac{q_{bal} \cdot l^2}{8f}$$

Deviation forces for full prestressing under load q_{bal}

$$u = 8\frac{P_\infty f}{l^2} \approx 0.8 \cdot q_{bal} \rightarrow P_\infty \approx \frac{0.8 \cdot q_{bal} \cdot l^2}{8f}$$

Superstructure / Girder bridges

Design and erection

Concrete girders

Erection methods and tendon layout

Concrete girders – Erection methods and tendon layout

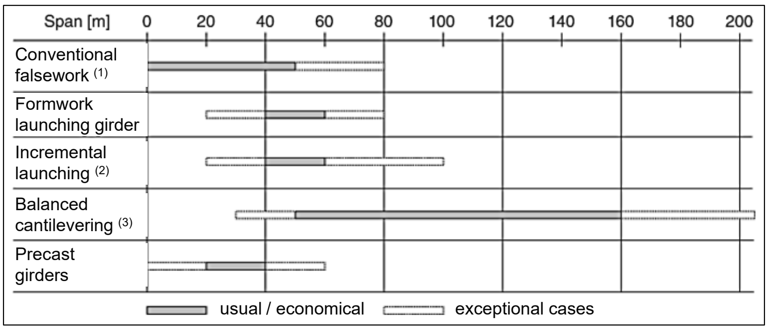
Prestressing concept

The prestressing concept, particularly the tendon layout and stressing sequence, are closely related to the erection method.

The erection method in turn depends on the

- span (see table)
- number of (equal) spans
- site (access, height above ground)
- preferences / expertise of contractor / designer

Concrete bridge erection methods



(1) usually most economical cast-in-place solution for low bridges with few spans
(2) requires suitable alignment (straight / circle / helix), economical for long bridges only
(3) economical for high bridges or spans crossing obstacles with restricted access

Table adapted from Reis Oliveiras, Bridge Design.

Superstructure / Girder bridges

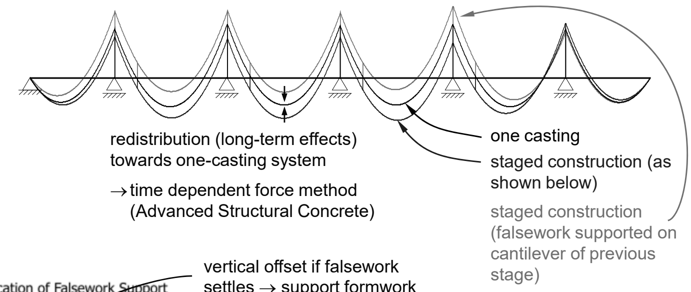
Design and erection
Concrete girders
Cast in place erection methods and tendon layout

Concrete girders – Cast in place erection methods and tendon layout

Erection on falsework (conventional falsework)

- The girder is cast on a temporary structure, which supports it until it resists on its own (after stressing of tendons)
- The falsework is supported on the ground
  → loads are transferred directly to the ground
  → economical for low height ($h \leq 10$ m)
  → usual spans up to 50 m (80 m in special cases)
  → access and stiff soil required; settlements at casting are problematic in staged construction (vertical offsets if falsework settles but bridge, sitting on final foundation, does not)

Moment line at t =0 (see Structural analysis – staged construction)



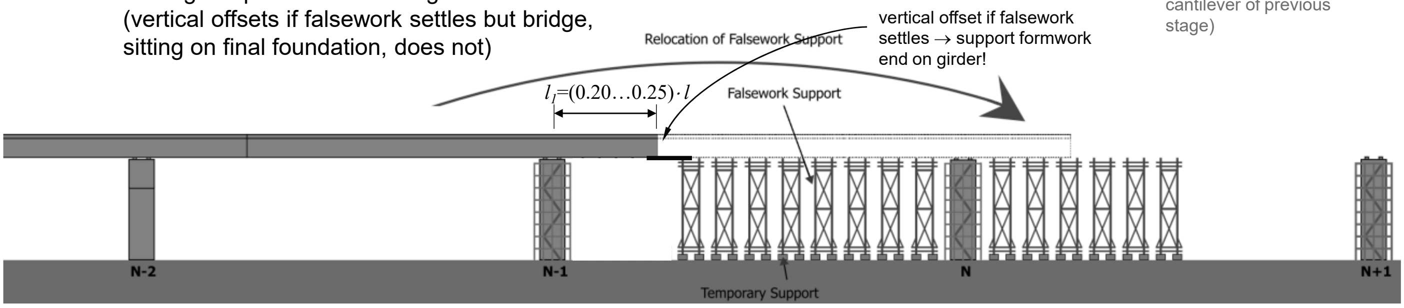


Illustration adapted from VSL Bridge Erection

Concrete girders – Cast in place erection methods and tendon layout

Erection on falsework (conventional falsework)

- Instead of a surface-type falsework, gantries on temporary support towers are often used (to bridge obstacles or for larger heights)

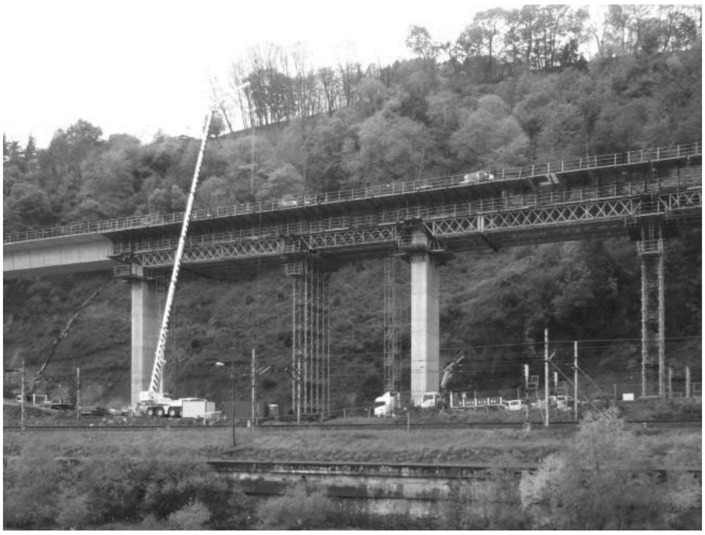


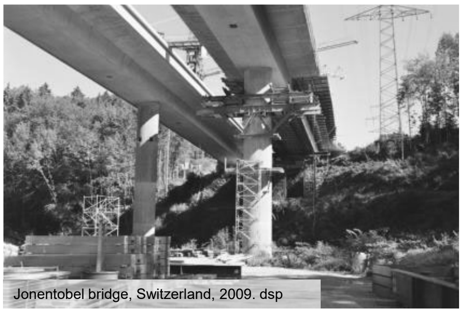
Photo: Tomas Vogel, Viadotto Preonzo-Claro (left); Viaductos de LAV. Tramo Tolosa-Hernialde, Spain © Fhecor Ingenieros (right)

Concrete girders – Cast in place erection methods and tendon layout

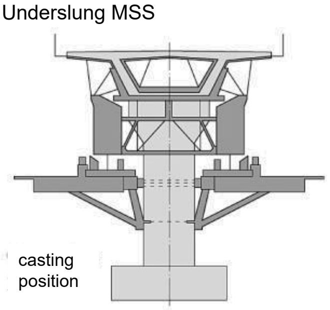
Movable Scaffold System MSS

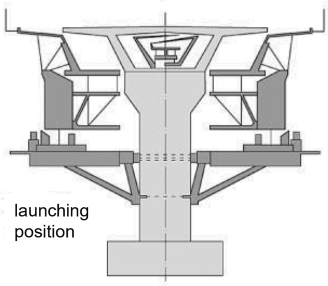
- An MSS is a launching gantry moving forward on the piers span by span
- Underslung and alongside MSS are supported on supports fixed to piers (“Steckträger”)
- Overhead MSS (more expensive) are supported on temporary elements over piers
- As much of the formwork as possible should move with the gantry but often
  … diaphragms obstruct interior formwork
  … piers obstruct soffit formwork → challenge
- Economical for
  → bridges with several equal (or at least reasonably similar) spans
  → multi-span bridges over obstacles or soft soil (no conventional falsework)
- Optimal span $30\ \mathrm{m} \le l \le 60\ \mathrm{m}$
  (> ca. 30 m with intermediate support)
- Tendon layout ≈ as conv. falsework


Viaduct over Deba river, Spain, 2015. IDEAM


Jonentobel bridge, Switzerland, 2009. dsp

Underslung MSS





Photos: IDEAM, Viaducto sobre el rio Deba (above); dsp, Jonentobelbrücke, Nationalstrasse A4a, Affoltern a/A ZH (below)

Ilustration: T. Siwowski, Bridge Engineering: Selected Issues, 2015

Concrete girders – Cast in place erection methods and tendon layout

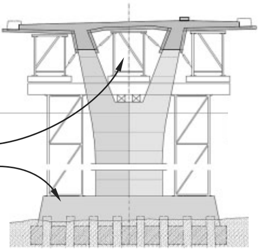
Movable Scaffold System MSS

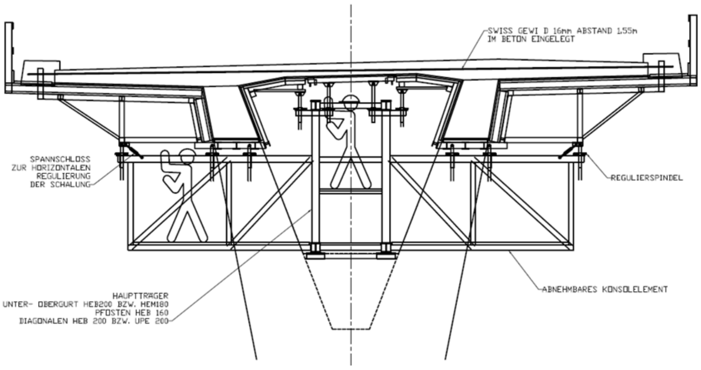
- Most economical solution depends on contractor's preference and availability of equipment (at location and time of tender)
- Example: Pier and foundations optimised for underslung triple beam MSS, contractor opted to move cantilever falsework with crane

Tender project

no diaphragms
pier openings
for MSS gantry

wide pile caps
for temporary
tower support





Steinbachviadukt, Switzerland, 2014. dsp

Steinbachviadukt, dsp (2014). Photos © dsp Ingenieure+Planer AG, Illustration © ARGE (Implenia/Kibag/Somaini

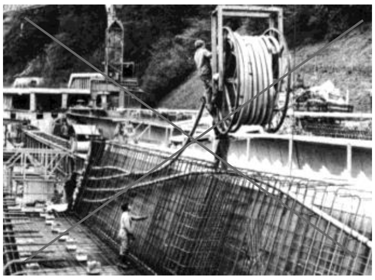
Concrete girders – Cast in place erection methods and tendon layout

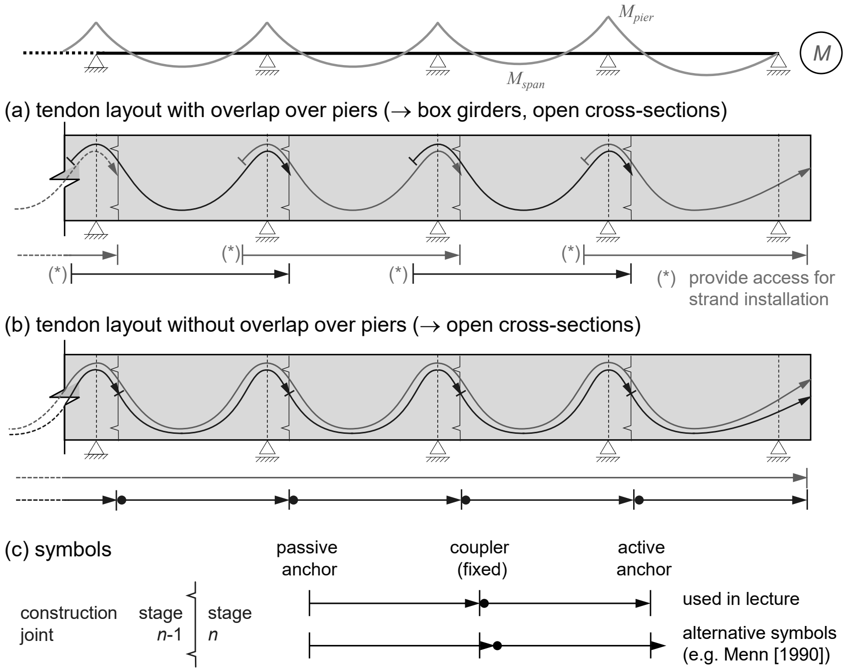
Tendon layouts for cast-in-place girders
(cast on conventional falsework or using MSS)

The figure shows possible tendon layouts for continuous girders built using conventional falsework or a movable scaffold system MSS.

Relevant aspects:

- provide access to active anchors
- as well as passive anchors of tendons not tensioned in the same stage as installed (enable strand installation, avoid coiled tendons on falsework)





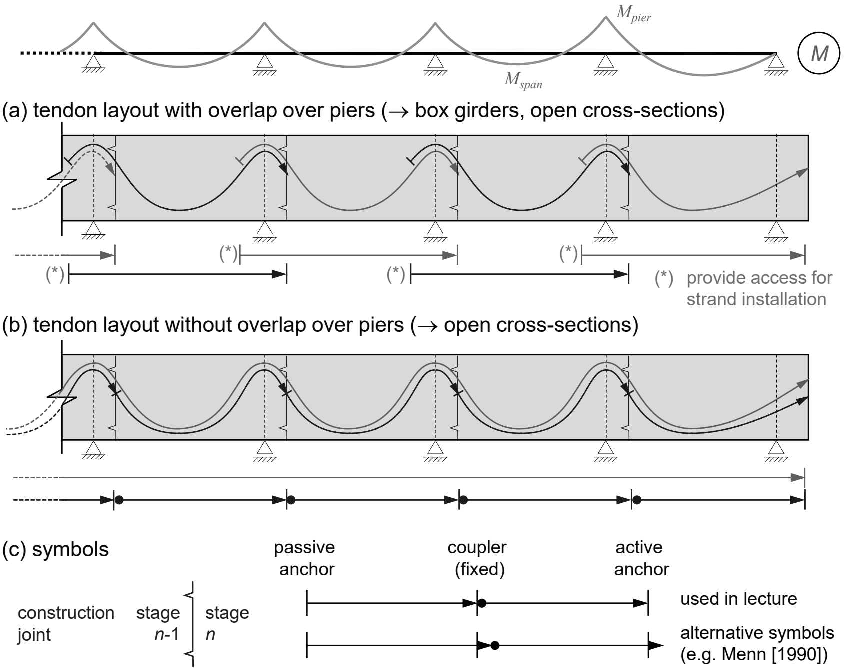
Note that in Alternative (b) shown in the slide, the tendons coupled at each construction joint must be sufficient for the construction stages, since the continuity tendons are only installed at the very end. Other solutions (e.g. with tendon families continuous over two or three spans) are possible, requiring access for strand installation as in Alternative (a).

Concrete girders – Cast in place erection methods and tendon layout

Tendon layouts for cast-in-place girders
(cast on conventional falsework or using MSS)

Relevant aspects (continued)

- Tendon profile ≈ moment diagram under permanent load (see load balancing)
- Layout (a): $A_{p,pier} = 2 \cdot A_{p,pier}$
  → efficient in ULS since $|M_{pier}| \approx 2 \cdot M_{span}$
- Layout (b) suitable for cross-sections with high centroid ($z_{sup} < z_{inf}$, e.g. T-beams):
  → W_{sup} (relevant over piers) > W_{inf}
  → large positive secondary moments due to predominantly positive eccentricity, i.e., less difference between M_{pier} and M_{span}
  → full prestressing for same load requires similar force P over piers as in span
- Avoid coupling all tendons at same joint where possible. If required, provide ample passive reinforcement A_s across anchorage zone ($A_s f_{sd} \approx A_p \sigma_{p0} /2$) (see notes)



If all tendons are coupled in the same construction joint, severe problems (fatigue, excessive cracking) may occur unless a strong passive reinforcement is provided. Several prestressed concrete bridges had to be strengthened for this reason, e.g. in Germany and Switzerland. Therefore, it is recommended to provide a relevant portion of the total prestressing force via continuous tendons («continuity tendons») at each construction joint (note that during construction, loads are lower and hence, about 50…70% of the total prestressing force is sufficient durcing construction unless heavy construction equipment (e.g. cranes) are supported on the girder before final prestressing.

The main reasons for these problems were that (i) couplers were (and are) usually provided near the points of zero moment due to vertical loads, and in the centroid of the cross-section; (ii) bending moments caused by temperature (gradients), which cause bending moments in the coupler region and may cause decompression, were neglected in design; and (iii) accordingly, hardly any passive reinforcement was provided in the regions of the couplers. Today, temperature gradients are commonly accounted for in the fatigue verifications of such regions reasons, and there are strict regulations in several countries (e.g., coupling all tendons in same construction joint prohibited).

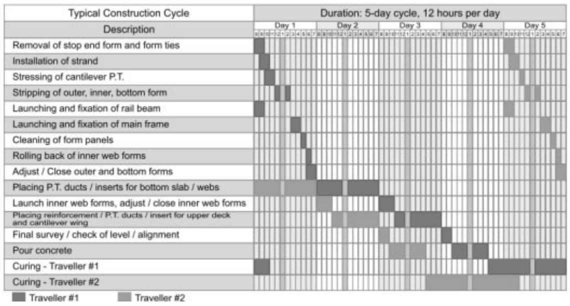
The stress state in the region of such construction joints is highly complex. Several effects (spreading of prestressing force = nonlinear strain distribution, creep, shrinkage, relaxation) are involved, which are difficult to quantify. Basically, the anchor force acts fully on the concrete cast in stage 1 until stage 2 is prestressed. At this moment, the coupled tendon pulls on the previously tensioned anchor, usually with a somewhat smaller force (due to friction losses). Thereby, the initially compressed region of stage 1 (loaded when stage 2 did not exist) is unloaded, but stage 2 is now active and monolithically connected to stage 1. The resulting stress state is complex and, as mentioned, varies due to long term effects. For fatigue verifications, it is however paramount to know whether the concrete in the anchor region is compressed (uncracked behaviour) or not.

As an order of magnitude, a passive reinforcement whose resistance corresponds to half the coupled prestressing force. In fatigue design, a lower bound value of the prestressing force should be assumed to act in the coupling region, and thermal gradients should be accounted for.

Concrete girders – Cast in place erection methods and tendon layout

Free / balanced cantilevering (*Freivorbau*)

- The girder is segmentally cast on a movable formwork cantilevering from the previously built segments
- Before installing the travellers, a pier table (*Grundetappe*) must be built on separate falsework
- Usually, two cantilevers are built ±symmetrically, starting from a pier (→ balanced cantilevering)
- Free cantilevering (smaller spans) is possible in other cases (e.g. right end span in example below)



(schedule assumes unbalanced moments of one element are admissible → cantilevers with ½ element offset; fully balanced construction requires casting of both cantilevers simultaneously)

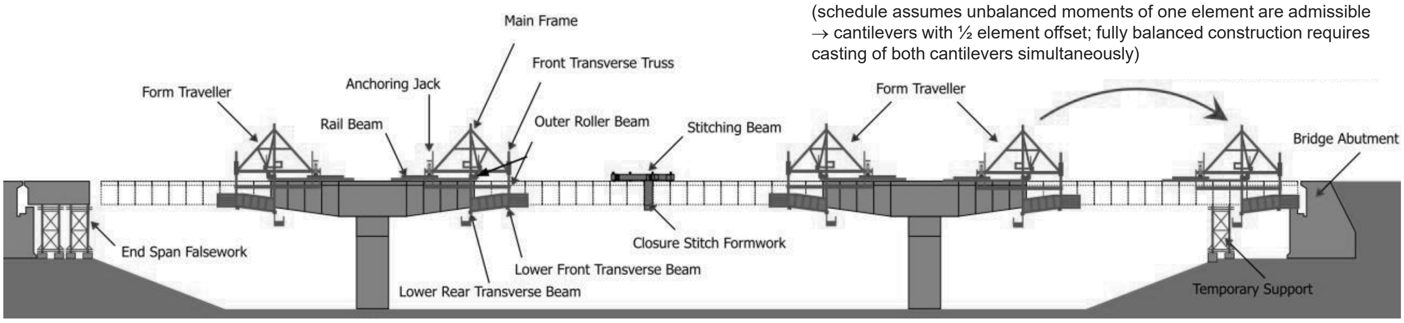


Photo: dsp, Innbrücke Vulpera

Illustration: Adapted from VSL Bridge Erection

Sources: VSL http://www.vsl.com/

Concrete girders – Cast in place erection methods and tendon layout

Free / balanced cantilevering (*Freivorbau*)

- Cantilevers are often symmetrical (→ cast both sides simultaneously) or have ½ element offset (→ faster, but unbalanced moment)
- Economical for medium-large spans only (high initial cost for pier table and travellers)
- Suitable for high bridges crossing obstacles or soft soil, with spans $70\ \mathrm{m} \leq l \leq 160\ \mathrm{m}$ (250 m in special cases)


Inn Bridge Vulpera, Switzerland, 2010. dsp

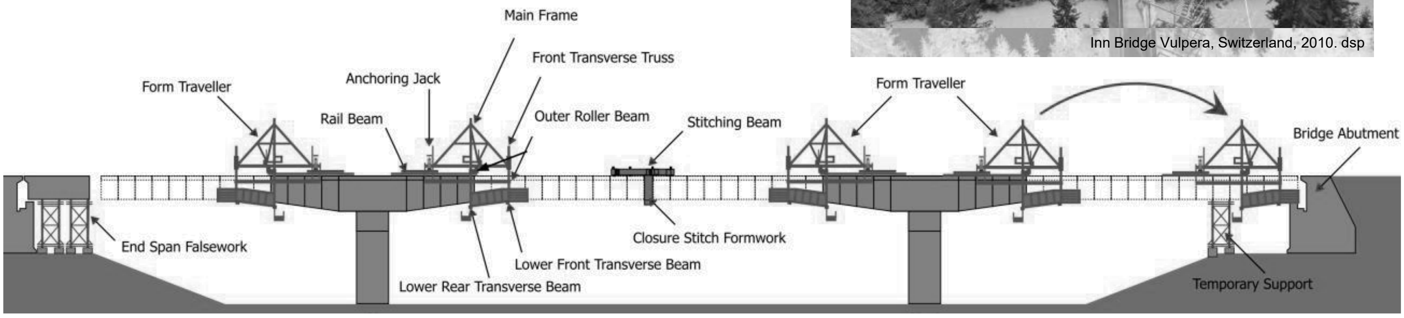


Photo: dsp, Innbrücke Vulpera

Illustration: Adapted from VSL Bridge Erection

Sources: VSL http://www.vsl.com/

Concrete girders – Cast in place erection methods and tendon layout

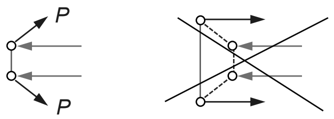
Tendon layouts for balanced cantilevering

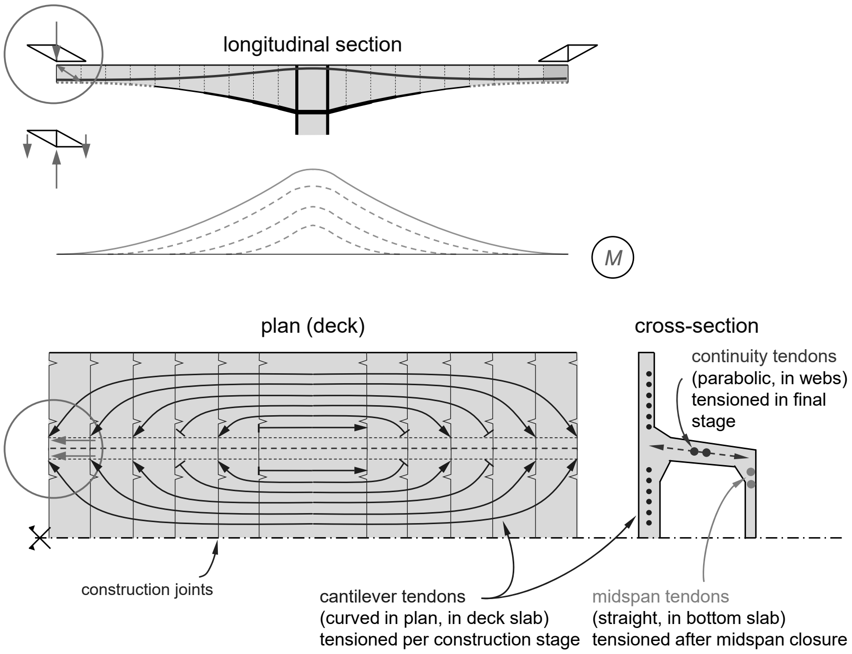
The figure shows a tendon layout for cast-in-place girders built by free cantilevering.

Relevant aspects:

- prestressing types (families):
  … cantilever tendons (essential)
  … midspan tendons (usual today)
  … continuity tendons (optional)
- anchor cantilever tendons near the webs
  → space for anchorages
  → longitudinal shear flow

The deck acts as tension chord, but the horizontal shear transferred to the deck cannot be spread via compressive forces (no «overhang» to accomodate struts):

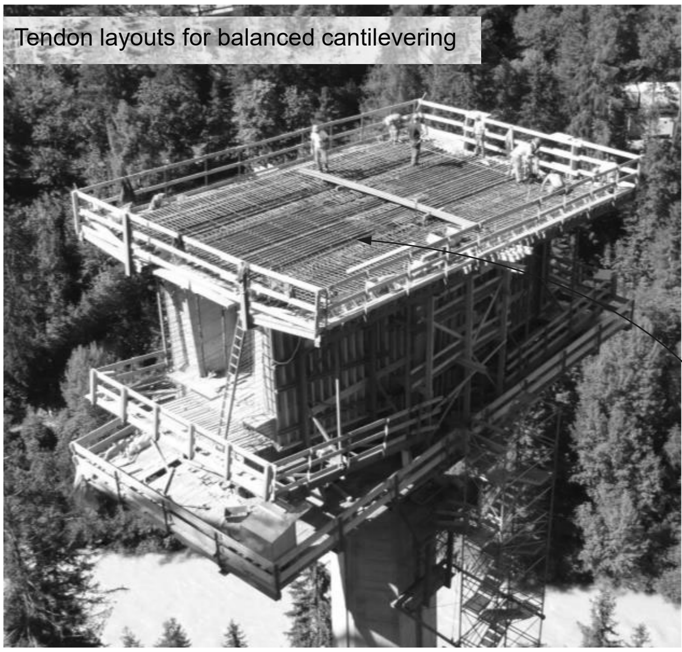




Note that in spite that the cantilever tendons are straight in elevation, they are rather acting as parabolic tendons due to the variable depth: With respect to the girder axis (centroid), they are indeed curved.

Naturally, the horizontal shear transferred away from the cantilever ends can be spread horizontally by compressive struts. However, significant horizontal shear forces need to be transferred close to the cantilever ends, where the traveller transfers a highly concentrated force at casting of the subsequent segment (depending on type of traveller, this may be more than twice the segment weight).

Concrete girders – Cast in place erection methods and tendon layout



cantilever tendons
(curved in plan, in deck slab)
tensioned per construction stage

continuity tendons
(parabolic, in webs)
tensioned in final stage

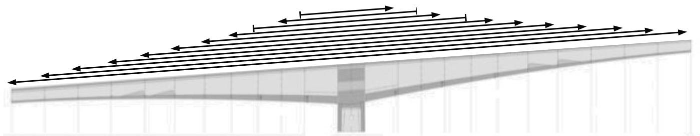
midspan tendons
(straight, in bottom slab)
tensioned after midspan closure

Concrete girders – Cast in place erection methods and tendon layout

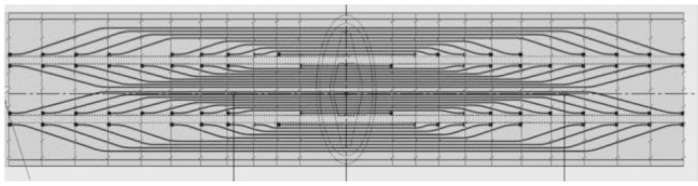
Tendon layouts for balanced cantilevering

cantilever tendons

longitudinal section



plan (deck)

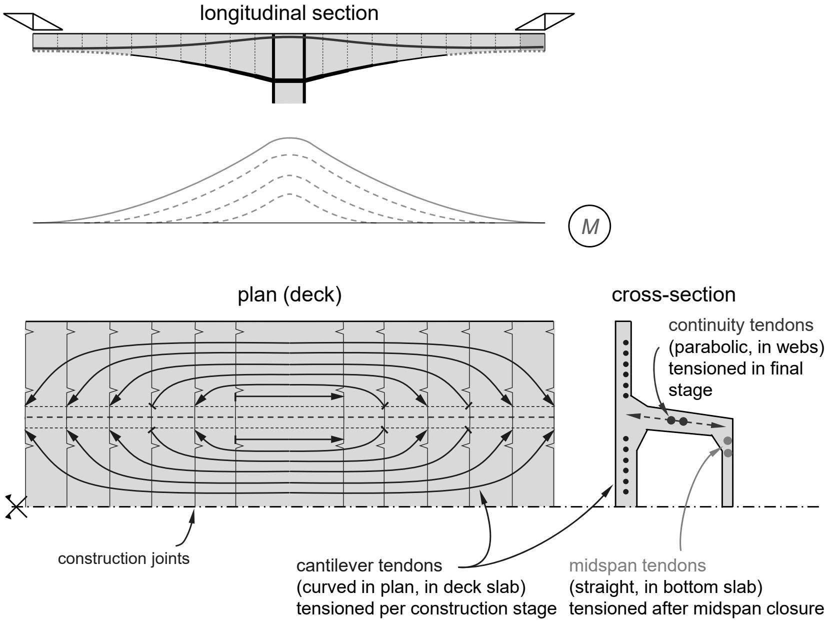


Concrete girders – Cast in place erection methods and tendon layout

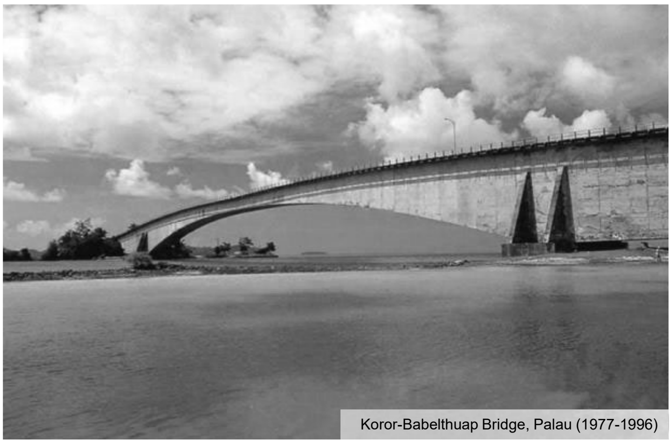
Tendon layouts for balanced cantilevering

Relevant aspects (continued):

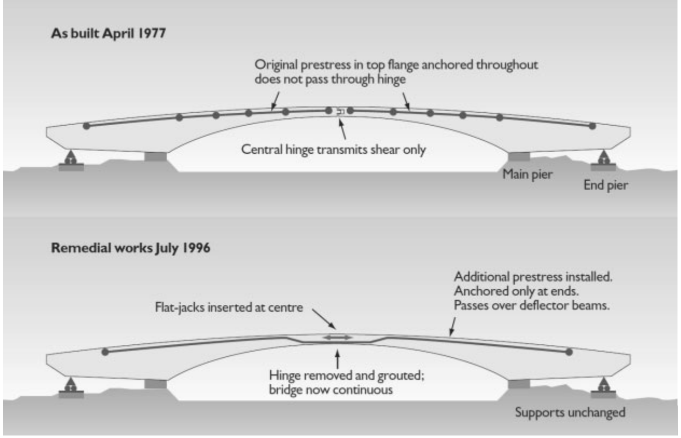
- Consider in-plan curvature of cantilever tendons when determining frictional losses (first ones may be stressed from one side)
- Midspan tendons are stressed from blisters inside box girder → provide access for jack
- Continuity tendons are long, with correspondingly high frictional losses and challenges for installation of strands
- Several early free cantilevered bridges experience excessive long-term deflections, potentially due to:
  - → lacking continuity (hinged at midspan, neither midspan nor continuity tendons)
  - → underestimation of frictional losses (horizontal curvature neglected)
  - → underestimation of creep (bottom slab often experiences high compressive stresses)

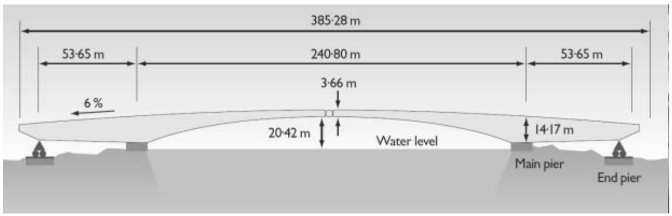


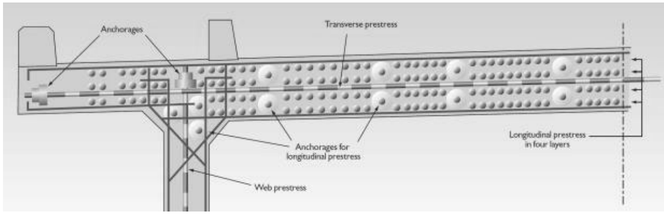
Concrete girders – Cast in place erection methods and tendon layout



Koror-Babelthuap Bridge, Palau (1977-1996)







In 1996, the Koror-Babelthuap Bridge in Palau, built 1977 (main span 240.8 m, world record span at the time for free cantilevered bridges), collapsed. The collapse occurred shortly after the bridge had been retrofitted due to excessive deflections; these had reached about 1.2 m in 1990 already, affecting the navigational clearance.

The excessive deformations were likely due to a combination of the causes listed on the previous slide. The bridge was articulated at midspan, had only cantilever tendons (bars) that were straight, but tensioned to relatively low values such that friction, creep and shrinkage lead to much higher relative losses than in tendons with higher initial stresses. Several authors attribute the collapse explicitly or implicitly to the excessive deformations, which is obviously not the direct cause since the bridge was retrofitted before collapse.

Based on a stress field analysis, it is evident that the bridge had insufficient capacity for longitudinal shear transfer, see cross-section. The most probable hypothesis is therefore a failure due to lacking longitudinal shear capacity. In other words: The bridge was standing for almost 20 years thanks to concrete tensile stresses transferring the longitudinal shear. When being retrofitted, the wearing surface and part of the deck were removed, causing vibrations that may have triggered the cracks leading to failure. All of this, is however merely a hypothesis – as in most failures, no one will ever know with absolute certainty what caused the collapse. There are merely probable and less likely causes (the deflections are not a probable one).

Illustrations: C. Burgoyne, R. Scantlebury. « Lessons learned from the bridge collapse in Palau». Civil Engineering 161, November 2008, pp. 28–34

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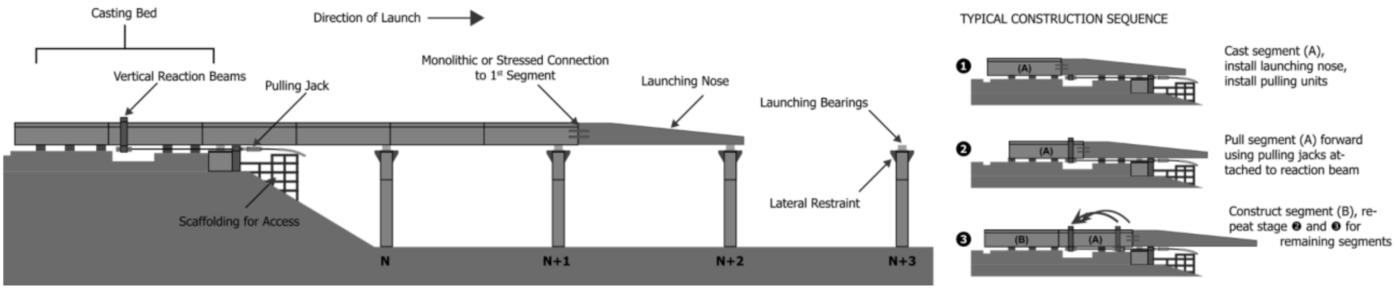
Concrete girders – Cast in place erection methods and tendon layout

Incremental launching ("precast on site")

- The girder is segmentally cast behind an abutment and launched over the piers using hydraulic jacks
- Segments cast and launched at a time (usually 15…30 m) are often shorter than a full span
- A launching nose, is required to limit (hogging) moment in the first segments. Additionally, temporary supports in long spans and stayed towers on the girder may be used
- The girder must have constant curvature and twist (possible geometries: straight, circular or helix, see notes)

Kürnach bridge, Germany, 2021. K+S Ingenieur-Consult



Bridges with a road alignments reasonably close to a straight, circle or helix with constant twist can be incrementally launched if the cantilever spans are varied such that the soffit matches the required geometrical criteria. This was for example done in the Viaduc Ile Falcon (see R. Favre et al., "Incremental Launching of the Ile Falcon Bridge", Concrete International Vol. 21, No. 2), 1999, pp. 46-51). note however that assuming a constant radius in plan as well as in elevation, as initially proposed for that bridge, does not yield a "launchable" geometry.

Photo: K+S Ingenieur-Consult, Kürnach bridge, Germany.

Illustration: Adapted from VSL Bridge Erection Brochure, http://www.vsl.com/

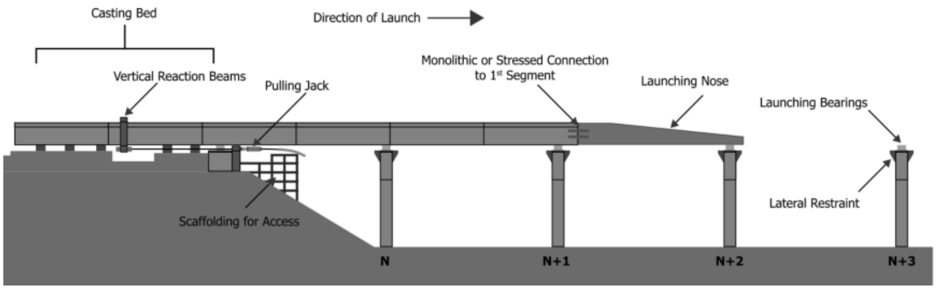
Concrete girders – Cast in place erection methods and tendon layout

Incremental launching (“precast on site”)

- Either temporary sliding bearings are used at all piers, or PTFE-coated boards are inserted between girder soffit and bearings
- Economical for long bridges crossing obstacles or soft soil, with spans $30\ \mathrm{m} \leq l \leq 60\ \mathrm{m}$
- High quality and fast construction speed achievable (casting yard may be equipped similar to precast concrete plant)

Löwenberg viaduct, Switzerland, 1993. GVH Tramelan

Typical Construction Cycle	Duration: 8-Day Cycle (Days)							
Description	1	2	3	4	5	6	7	8
Launch Segment								
Strip and Clean Forms								
Install Base and Web Rebar								
Install Web Forms								
Concrete Base and Webs								
Install Inner Forms								
Install Top Slab Rebar								
Concrete Top Slab								
Curing								
Stress P.T.								



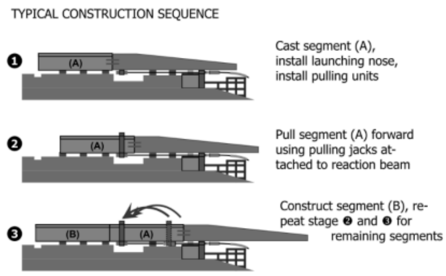


Photo: Tomas Vogel

Illustration: Adapted from VSL Bridge Erection

Further reading:

- B. Göhler, B. Pearson: Incrementally Launched Bridges: Design and construction, Ernst&Sohn, 2000
- M. Rosignoli, Bridge Launching, Thomas Telford, 2002

Concrete girders – Cast in place erection methods and tendon layout

Tendon layouts for incrementally launched girders

- During launching, every section (except in the last segments) experiences positive and negative bending moments
- The moment envelope (extreme bending moments at each point along the girder axis) is governed by the longest span a section has crossed during launching
- Launching moments are fairly constant but change sign
  → straight launching tendons in deck top and bottom slab
  → additional web tendons (parabolic) as required for final stage
- The figure shows one of many possible tendon layouts (contractor and designer preferences vary)

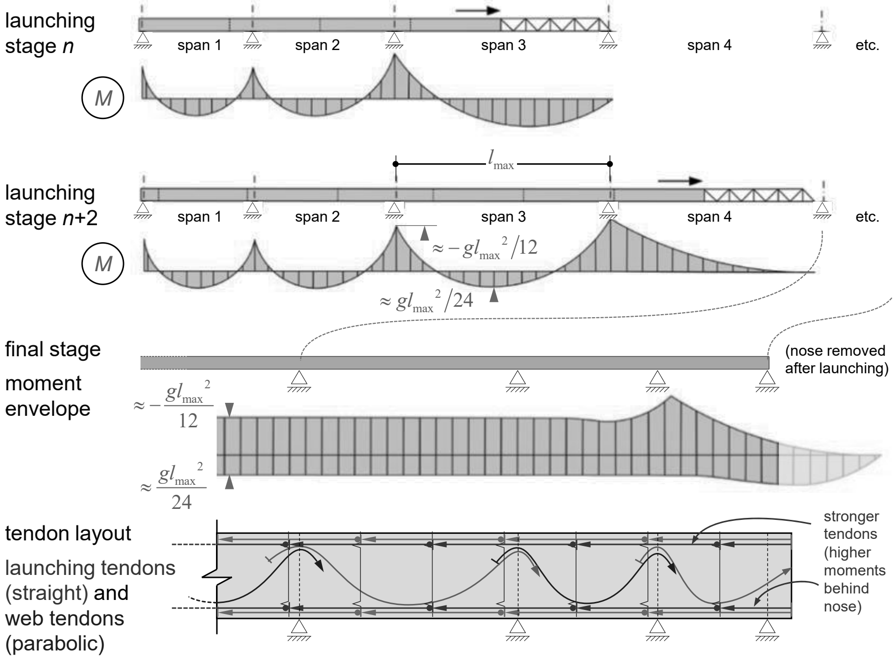


Illustration adapted from Reis Oliveiras, Bridge Design.

Further reading:

- B. Göhler, B. Pearson: Incrementally Launched Bridges: Design and construction, Ernst&Sohn, 2000
- M. Rosignoli, Bridge Launching, Thomas Telford, 2002

Superstructure / Girder bridges

Design and erection

Concrete girders

Precast girder erection methods and prestressing layout

Concrete girders – Precast girder erection methods and prestressing layout

General remarks and slenderness

- The girders are precast in a prefabrication plant
  → high quality and efficient production
- The precast girders are delivered by road or over the previously erected part of the bridge
- The full span precast girders are installed using
  … cranes
  … overhead gantries
  … launching carriers
- Economical for bridges with many (almost) equal spans, usually ≥ 40 precast elements)
- Spans are limited to about $l \leq 30$ m due to
  … maximum transportable length (road < carrier)
  … lifting capacity of cranes < gantries < carriers
- The slenderness h/l depends on the span and the transverse girder spacing, usually:

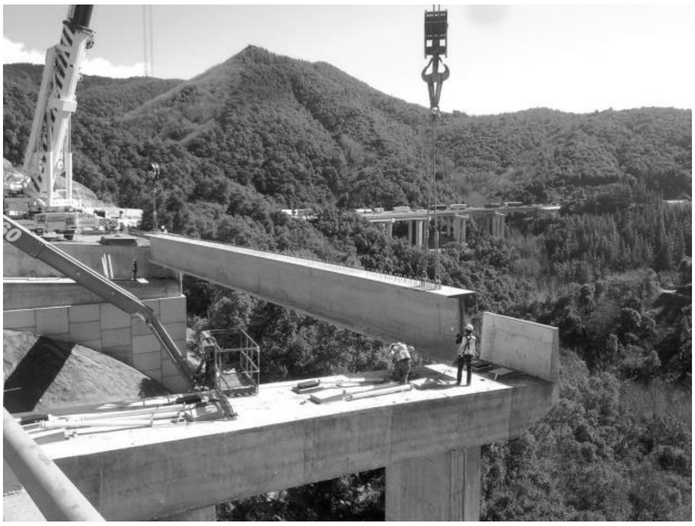
$$\frac{1}{20} \leq \frac{h}{l} \leq \frac{1}{15}$$

Photos: ARUP http://www.arup.com

Concrete girders – Precast girder erection methods and prestressing layout

Lifting with cranes

- Suitable for sites with easy access for trucks and cranes (girder delivery and lifting)
- More flexible (e.g. curved alignments), but less efficient than overhead gantries and launching carriers
- limited element weights (crane capacity)



Photos: left: © ARUP; right: Desdoblamiento ctra. C-25 (Espinelves-Santa Coloma de Farnes), Spain © Pacadar SL

Concrete girders – Precast girder erection methods and prestressing layout

Installation with overhead gantry

- Suitable for sites with easy access for trucks (girder delivery)
- More efficient than lifting by cranes
- Limited flexibility for curved alignments

Typical Erection Cycle	Duration: 2-Shift Cycle (Hours)	
Description	Shift - 1 (10 Hour Shift)	Shift - 2 (10 Hour Shift)
Lift and place 1st beam (outer most) with precast plank on top		
Lift and place 2nd beam with precast plank on top		
Lift and place 3rd beam with precast plank on top		
Lift and place 4th beam with precast plank on top		
Reposition the intermediate planks into final position		
Move gantry to center viaduct then launch to next span		

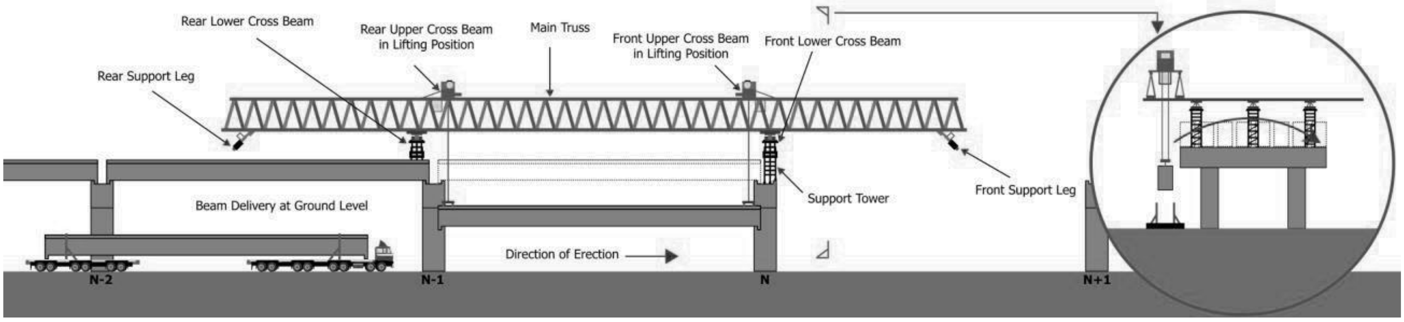


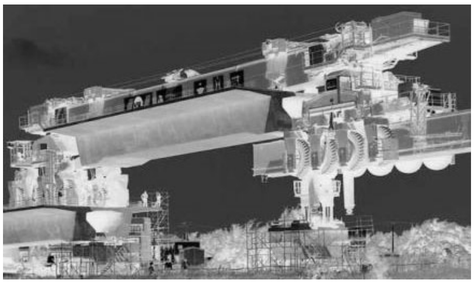
Illustration and photo adapted from VSL Bridge Erection

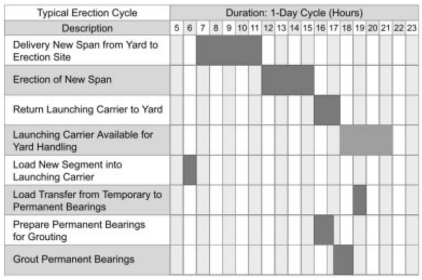
Sources: VSL http://www.vsl.com/

Concrete girders – Precast girder erection methods and prestressing layout

Full span precast method
(launching carrier / VSL)

- Girder delivery via previously built bridge
  → no access for trucks required
  → girders may be heavier and longer than in other methods
- Highly efficient, but very limited flexibility for curved alignments





The illustration below shows the situation after the support beam has been moved ahead (= photo).
Before moving the support beam, the front trailer travels along the span between Piers N and N+1 on the support beam.

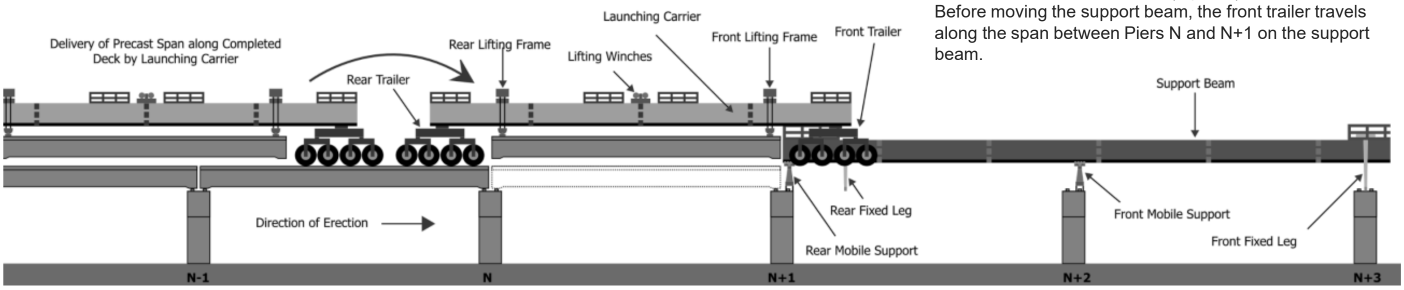


Illustration and photo adapted from VSL Bridge Erection

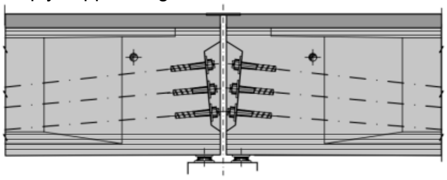
Sources: VSL http://www.vsl.com/

Concrete girders – Precast girder erection methods and prestressing layout

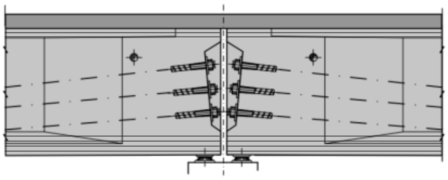
Prestressing layout for precast girder bridges
(see also “precast girders - arrangement over supports”)

- Basically, precast girders have similar prestressing layouts as cast in place bridges
- Tendon layouts need to be compatible with the arrangement of joints
- Precast girders are often pretensioned (with strands or wires) at least for their self-weight, rather than posttensioned
- Simply supported girders and girders with partial continuity may be:
  … only pretensioned
  … pretensioned with additional, usually parabolic tendons (need to be tensioned before next girder is positioned, constraint for construction)
  … only with posttensioning tendons (applied before delivery, force may be increased on site)
- In girders with full continuity, additional tendons are required to resist hogging moments (arranged in top slab over piers)

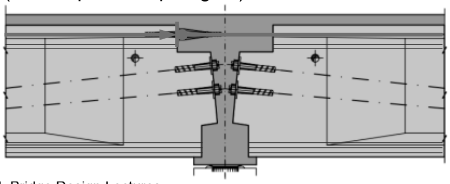
Independent, simply supported girders



Partial continuity (monolithic deck slab)



Full continuity (cast-in-place diaphragms)



Superstructure / Girder bridges

Design and erection
Concrete girders
Precast segment erection methods and tendon layout

Concrete girders – Precast segment erection methods and tendon layout

General remarks on precast segmental bridges

- The segments are produced in a casting yard by match-casting:
  Segment n-1 (and a stiff stop formwork) = formwork for Segment n
  … short line (all segments cast in same position)
  … long line (segments cast in position / span, control of geometry)
  → high quality and efficient production
- Precast segments are delivered by road or over the previously erected part of the bridge
- Precast segments are installed using
  … cranes and conventional falsework
  … overhead gantries or lifting frames
- The joints between segments are unreinforced, but provided with shear keys (and fully prestressed for g+p)
- The segments are assembled dry (durability?) or using epoxy resin; post-tensioning tendon ducts need to be coupled as well
- Economical for long bridges (viaducts) with many similar spans (same cross-section of girder)
- The segment length is limited by transport capacities (economic span depends on method, see behind)

Photos: J.E. Kristensen, Precast Segment Manufacturing, www.suncam.com

Concrete girders – Precast segment erection methods and tendon layout

Erection on falsework
(span by span)

- The segments are assembled on a temporary structure, which supports them until they resist on their own (after stressing the tendons)
- Access for trucks and crane required
- Suitable for stiff soil and low height
- Settlements can be adjusted
- Economic span ca. $l \leq 50$ m
  (80 m in special cases)

Typical Erection Cycle	Duration: 4-Day Cycle (Days)			
Description	1	2	3	4
Installation of Scaffold Support				
Erection of Segments				
Alignment and Gluing				
Post Tensioning Operations				
Load Transfer onto Permanent Bearings				

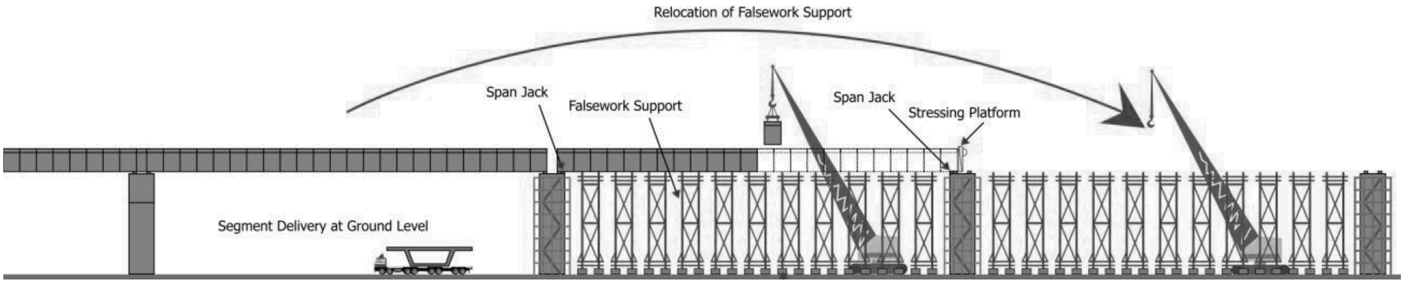


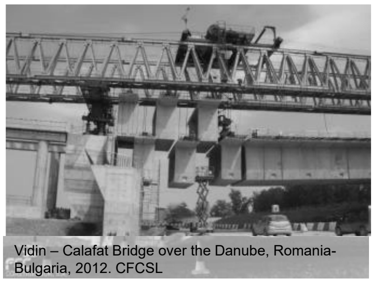
Photo and illustration adapted from VSL Bridge Erection

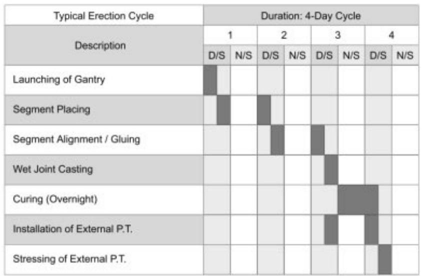
Sources: VSL http://www.vsl.com/

Concrete girders – Precast segment erection methods and tendon layout

Erection with launching gantry
(span by span)

- Suitable for sites with access for trucks unless segments are delivered via bridge
- More efficient than erection on falsework
- Limited flexibility for curved alignments
- Economic span ca. $25\ \mathrm{m} \leq l \leq 45\ \mathrm{m}$


Vidin – Calafat Bridge over the Danube, Romania-Bulgaria, 2012. CFCSL



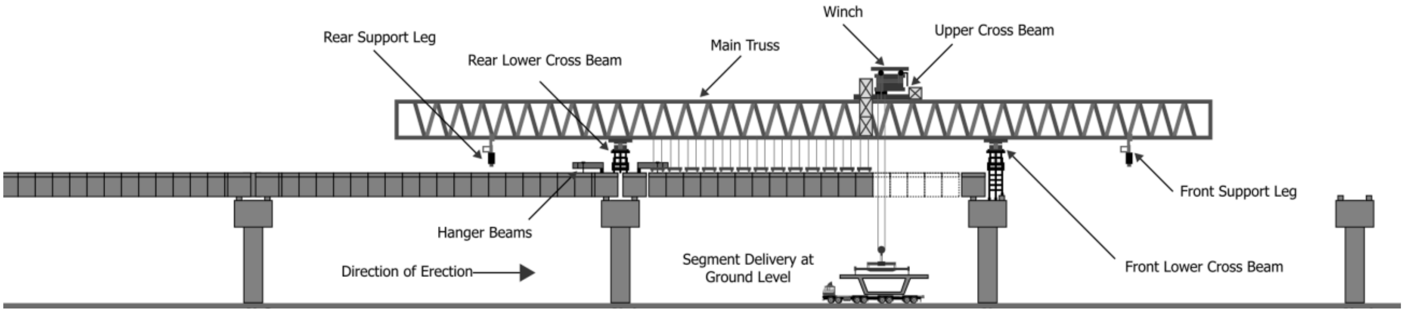


Photo: Vidin – Calafat Bridge over the Danube, Romania-Bulgaria, 2012 © Carlos Fernandez Casado S.L.

Illustration adapted from VSL Bridge Erection

Sources: VSL http://www.vsl.com/

Concrete girders – Precast segment erection methods and tendon layout

Free / balanced cantilevering
with cranes

- Suitable for sites with access for trucks and cranes over entire length of bridge
- Segment weight limited by transportation and crane capacity
- Suitalbe for low-moderate height (< 10 m)
- Economic span ca. $45 \text{ m} \leq l \leq 135 \text{ m}$
- High flexibility for curved alignments

Typical Erection Cycle	Duration: 8 Shifts							
Description	1	2	3	4	5	6	7	8
Installation of Pier Segment Support Brackets	■	■	■					
Installation of Pier Segment				■				
Segment Erection - Pair 1-3					■			
Segment Erection - Pair 4-6						■		
Segment Erection - Pair 7-9							■	
Segment Erection - Pair 10-12								■

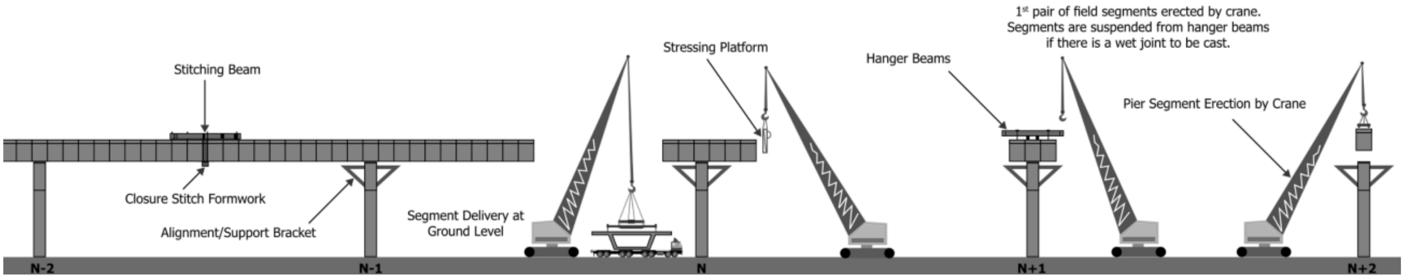


Photo and illustration adapted from VSL Bridge Erection

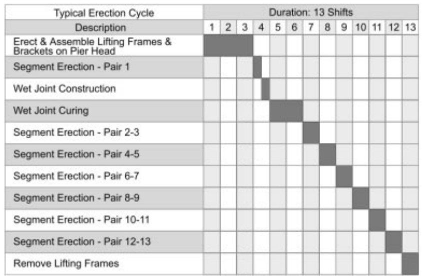
Sources: VSL http://www.vsl.com/

Concrete girders – Precast segment erection methods and tendon layout

Free / balanced cantilevering
with lifting frames

- Suitable for sites with access for trucks over entire length of bridge
- High lifting capacity of frames → large segments possible
- Economic span ca. $45\ \mathrm{m} \leq l \leq 135\ \mathrm{m}$
- High flexibility for curved alignments


Vidin – Calafat Bridge over the Danube, Romania-Bulgaria, 2012. CFCSL



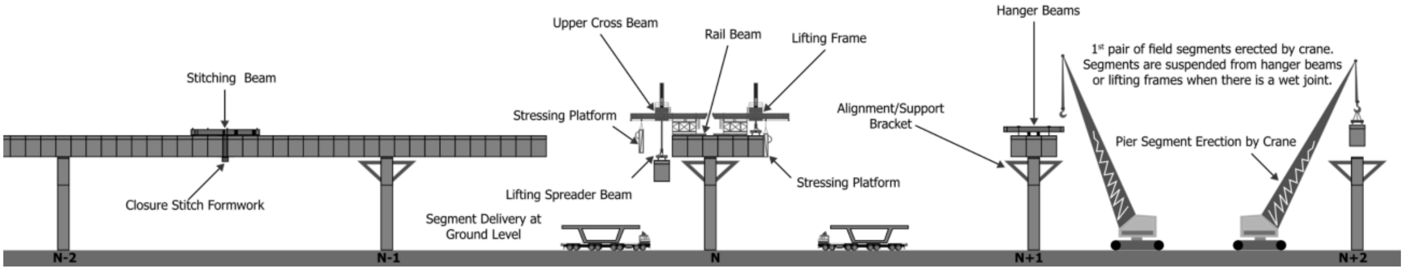


Photo: Vidin – Calafat Bridge over the Danube, Romania-Bulgaria, 2012 © Carlos Fernandez Casado S.L.

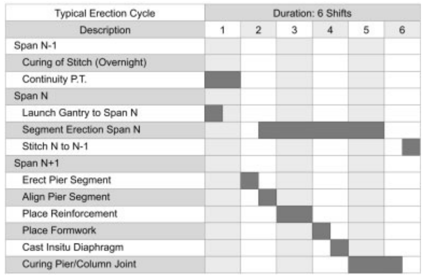
Illustration adapted from VSL Bridge Erection

Sources: VSL http://www.vsl.com/ and BBR https://www.bbrnetwork.com/)

Concrete girders – Precast segment erection methods and tendon layout

Free / balanced cantilevering
with launching gantry

- Suitable for sites with access for trucks unless segments are delivered via bridge
- More efficient than erection on falsework, lighter gantry than for span-by-span erection
- Limited flexibility for curved alignments
- Economic span about $25\ \mathrm{m} \leq l \leq 45\ \mathrm{m}$



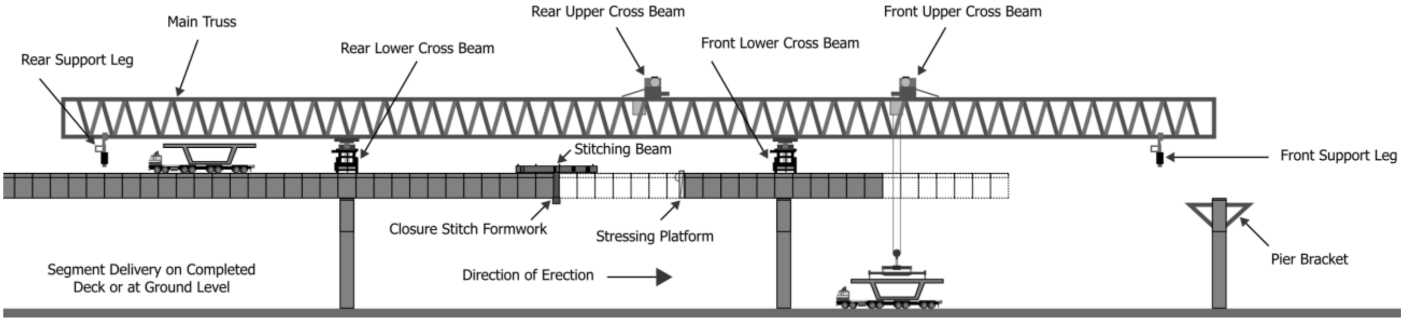


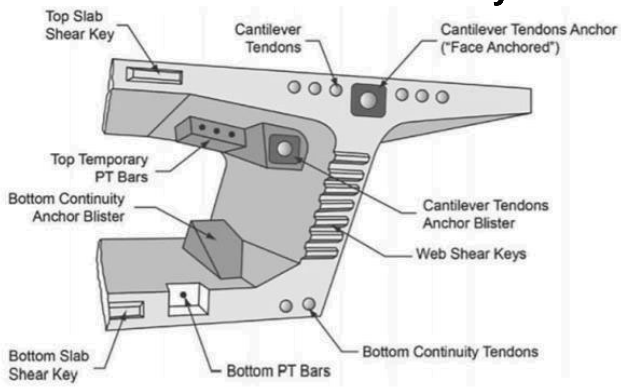
Illustration adapted from VSL Bridge Erection. Photo © http://www.huadacrane.com/

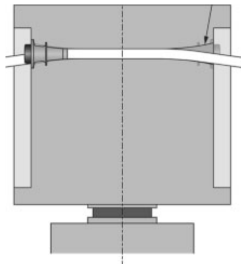
Sources: VSL http://www.vsl.com/

Concrete girders – Precast segment erection methods and tendon layout

Tendon layout

- External tendons are preferred in span-by-span segmental construction (internal post-tensioning ducts complicate joint detailing)
- Continuity of external tendons achieved by tendon overlap in pier segments
- Temporary prestressing (prestressed bars) is used for assembly (epoxy is squeezed out at stressing)
- To avoid joint opening in service (durability, appearance), precast segmental bridges require a higher level of prestress (fully prestressed for dead load and live loads, neglecting tensile strength of epoxy in joints)
- In ULS, opening of the joints is permitted and the increase of the forces in external tendons may be accounted for by adding
  … the integral of curvatures between joints
  … the joint openings at the level of the tendons
  for each tendon (simple models yield quite accurate predictions); see notes for design guidelines.





Top: Segment for cantilevered construction (with internal tendons) © ASBI, see further reading
Bottom right: External tendons inside a segmental box girder © BBR PTE
Bottom left: Overlap of external tendons in pier segment © ASBI

Further reading

Design:

- AASHTO Guide specifications for design and construction of segmental concrete bridges, 1999
- A. Specker.,"Der Einfluss der Fugen auf die Querkraft-und Torsionstragfähigkeit extern vorgespannter Segmentbrücken". Diss. Technische Universität Hamburg, 2001

Construction methods:

- American Segmental Bridge Institute ASBI, Construction Practices Handbook for Concrete Segmental and Cable-Supported Bridges, 2019 (free download from https://www.asbi-assoc.org/)
- VSL Bridge Erection

Experimental Testing and validation of calculation models for tendon force increase:

- T Takebayashi, K Deeprasertwong und YW Leung. "A full-scale destructive test of a precast segmental box girder bridge with dry joints and external tendons." *Proceedings of the Institution of Civil Engineers, S*tructures and Buildings 104.3 (1994), pp.. 297–315
- A. Weis, "Fugentragverhalten bei zusammengesetzten Elementen, MSc thesis, ETH Zurich, Chair of Concrete Structures and Bridge Design, 2018.