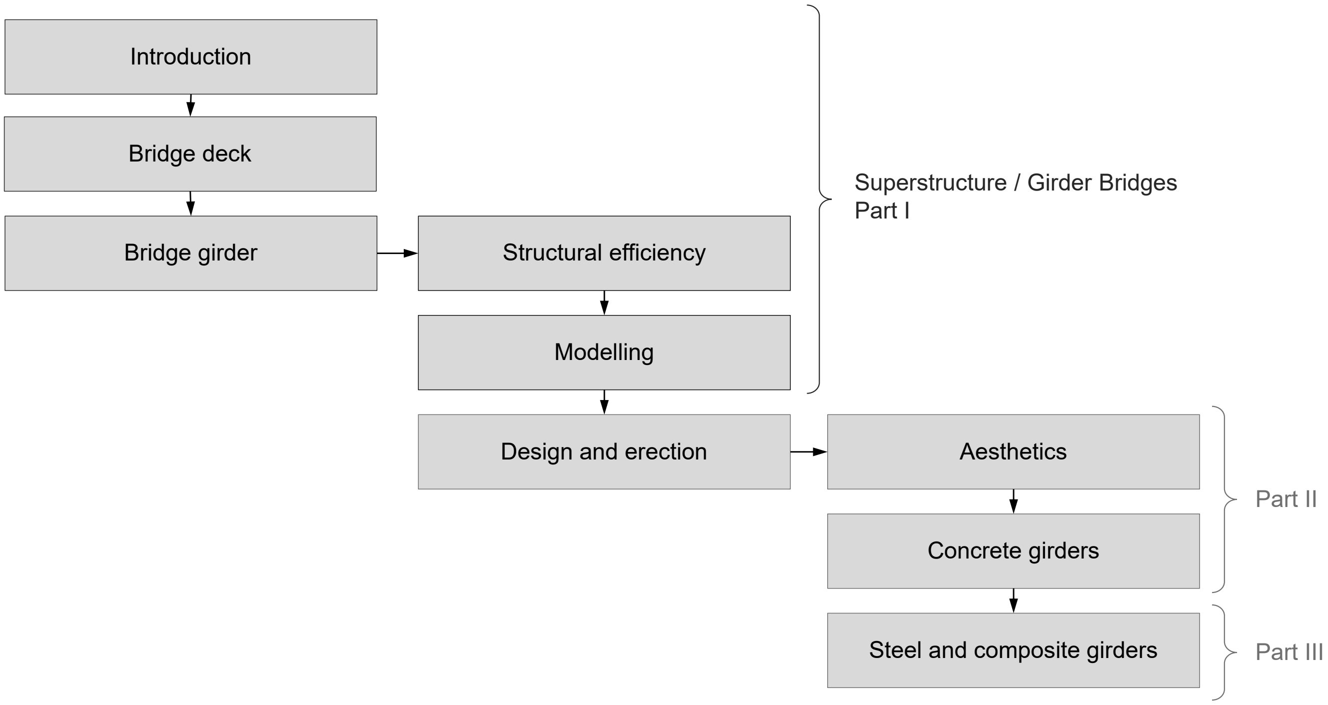
Superstructure / Girder bridges

Design and erection


Introduction
Bridge deck
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Superstructure / Girder bridges

Design and erection
Design – Aesthetics

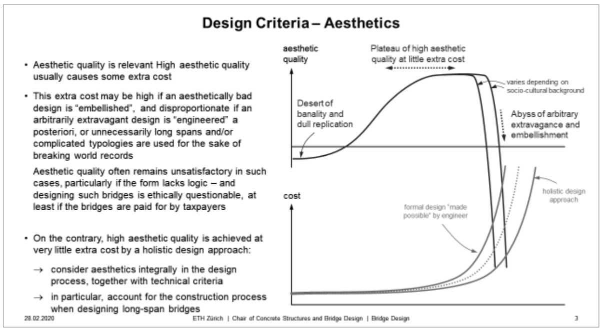
Design – Aesthetics

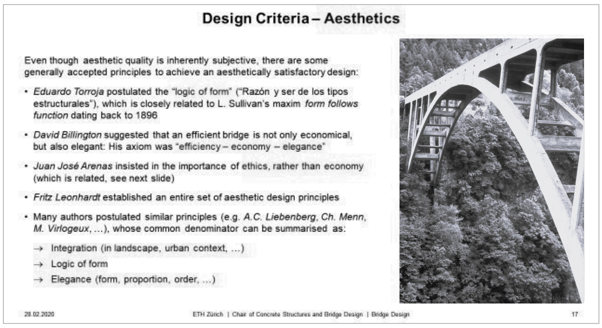
- Aesthetic quality is an important design criterion, see Conceptual Design, Design Criteria – Aesthetics:
  - → Bridge designers are responsible for the aesthetic quality of their bridges, as much as for structural safety and serviceability
  - → Even though aesthetic quality is inherently subjective,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

Photos © https://commons.wikimedia.org/w/index.php?curid=4561898

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)

KW1

Design – Aesthetics

Apparent slenderness – Proportion

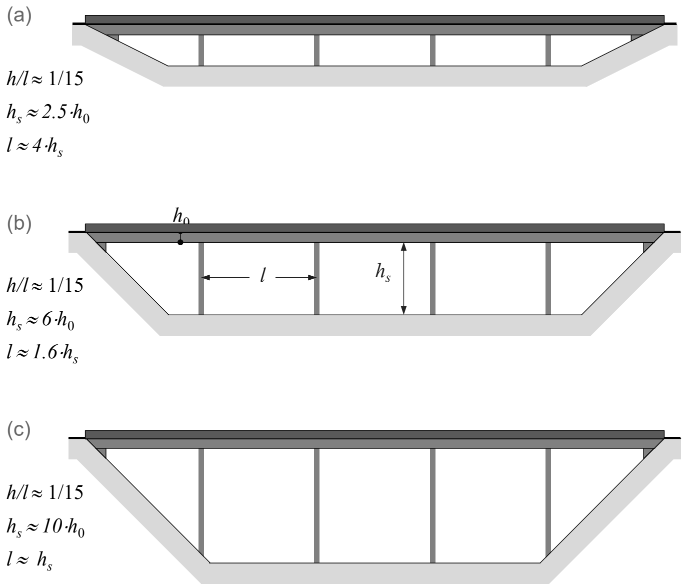
- Low bridges appear more massive than high bridges, even if they have equal span and slenderness (see figures, example with $h/l \approx 1/15$)

→ 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, …)



KW1

Design – Aesthetics

Apparent slenderness – Proportion

- 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)

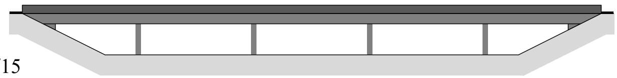
Figures (a)…(c) have
- equal PGL height above ground (low height)
- equal structural slenderness h/l
- variable span (and depth since h/l = const.)
- optional non-structural elements (noise barriers, concrete barriers, …)

(a)

$h/l \approx 1/15$
$h_s \approx 5\ h_0$
$l \approx 2.5\ h_s$

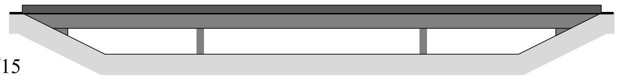
Low bridges: Maximise clear height
→ Choose short spans enabling slender girder

(b)



$h/l \approx 1/15$
$h_s \approx 2.5\ h_0$
$l \approx 4\ h_s$

(c)



$h/l \approx 1/15$
$h_s \approx 1.5\ h_0$
$l \approx 9\ h_s$

Design – Aesthetics

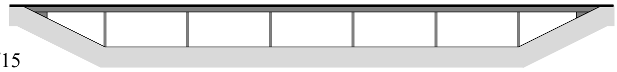
Apparent slenderness – Proportion

- 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

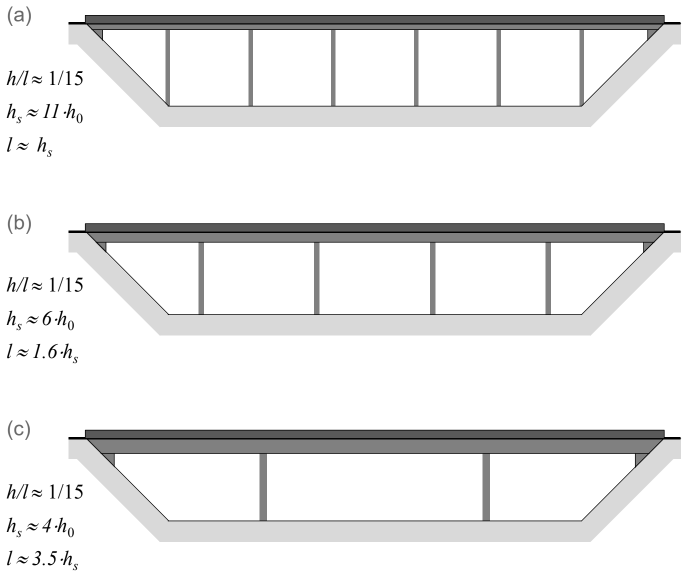
Design – Aesthetics

Apparent slenderness – Proportion

- 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, …)



KW1

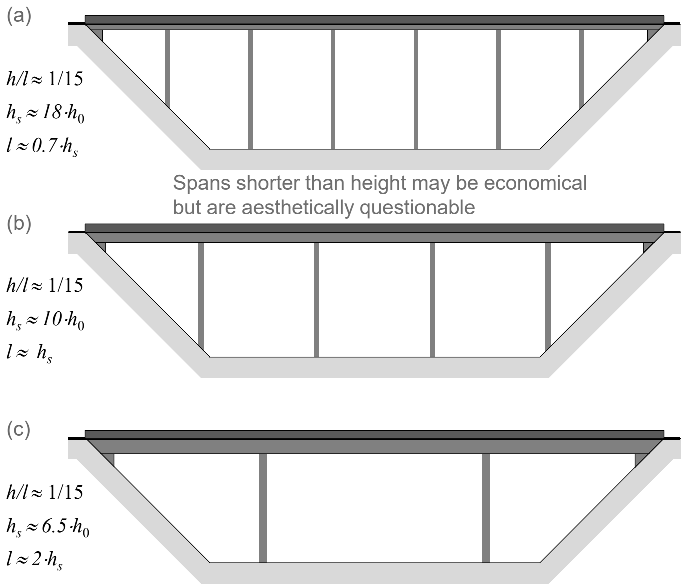
Design – Aesthetics

Apparent slenderness – Proportion

- 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, …)

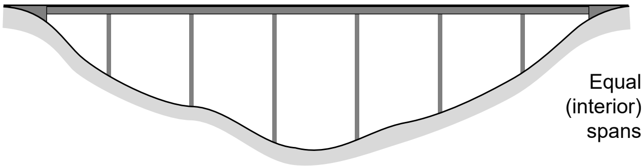


KW1

Design – Aesthetics

Apparent slenderness – Proportion – Span layout

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



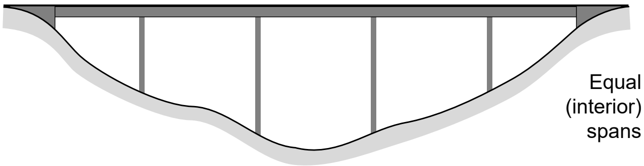


Photo: Viaducto del Istmo (2008). Spans 52+10x66 + 52 m © CFCSL

Design – Aesthetics

Apparent slenderness – 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

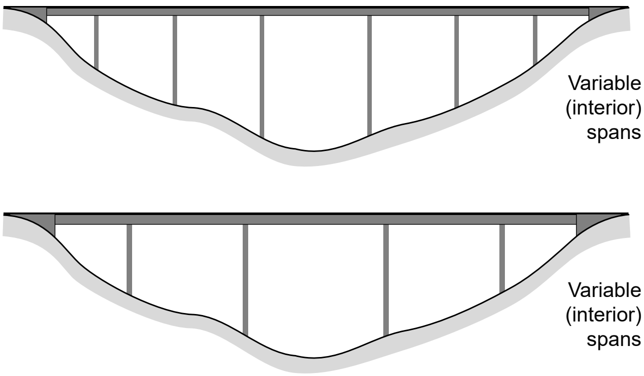


Photo Umfahrung Wattwil, Brücke Thur/SOB, Synaxiy and Gerber Partner (2020). Spans and girder depth increasing from abutments to middle of bridge. © Synaxis

Design – Aesthetics

Apparent slenderness – 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)

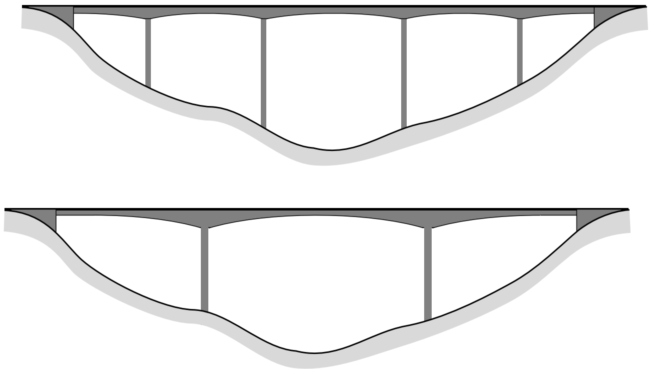


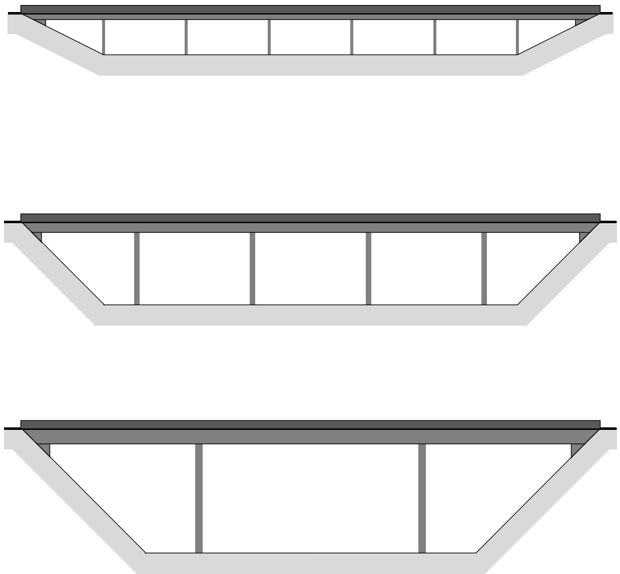
Photo: Viaducto de Montabliz, Cantabria, Spain, Apia XXI (2008). Spans 110+155+175+155+126 m, Maximum pier height 145 m Photo © Ferrovial

KW1

Design – Aesthetics

Apparent slenderness – Proportion

- 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



(middle figure more or less corresponds to golden ratio of span/height = 1.618, but this is hardly ever possible due to site constraints: the number of spans must match the topography)

Design – Aesthetics

Apparent slenderness – Non-structural elements

- 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

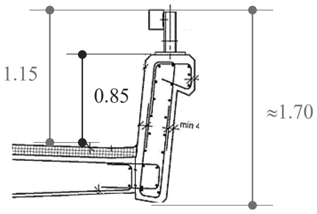


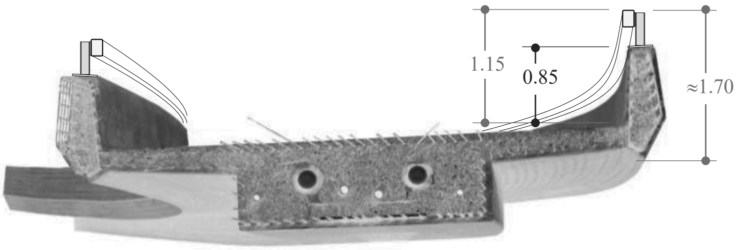
Photo: right side Einfahrtsrampe BW714, Dreieck Zürich West, length 120 m, spans 4x29 m (side span = interior span), dsp Ingenieure + Planer AG, 2004 © W. Kaufmann

bottom:

Design – Aesthetics

Apparent slenderness – Non-structural elements

- 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 attached guide rail (aufgesetzter Leitholm), e.g. 0.85+0.30 m, see below

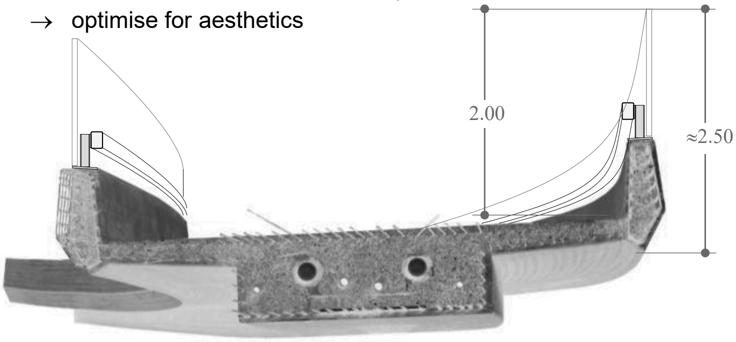


Photos: Zurich Airport, access ramps, dsp (1998-2008). Photos © dsp Ingenieure + Planer

Design – Aesthetics

Apparent slenderness – Non-structural elements

- 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 – Non-structural elements

- 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) except in special cases, see photos.

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 – contrast and rhythm

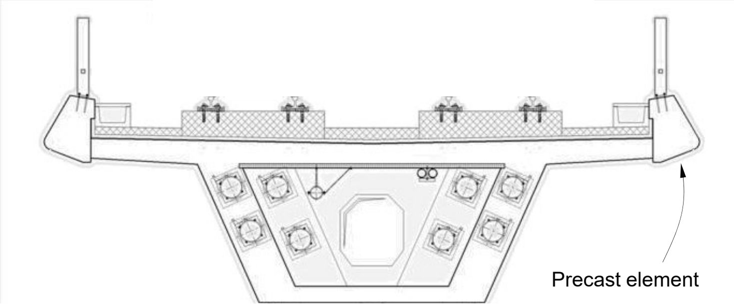
- The apparent slenderness of bridge girders can be significantly enhanced by making use of rhythm and contrast (light and shadow)
- If wide cantilevers are provided, much of the girder depth will be in the shadow, while the parapets / edge beams are much brighter (even on overcast days or at night)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

- 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 – contrast and rhythm

- 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

Apparent slenderness – contrast and 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

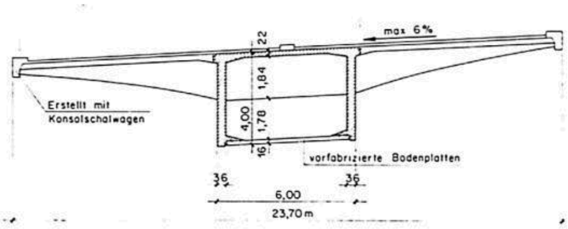
Bottom: Puente sobre la Ría de Betanzos, La Coruña, ES, Juan José Arenas (1996). Photo © Arenas y Asociados

Design – Aesthetics

Apparent slenderness – contrast and rhythm

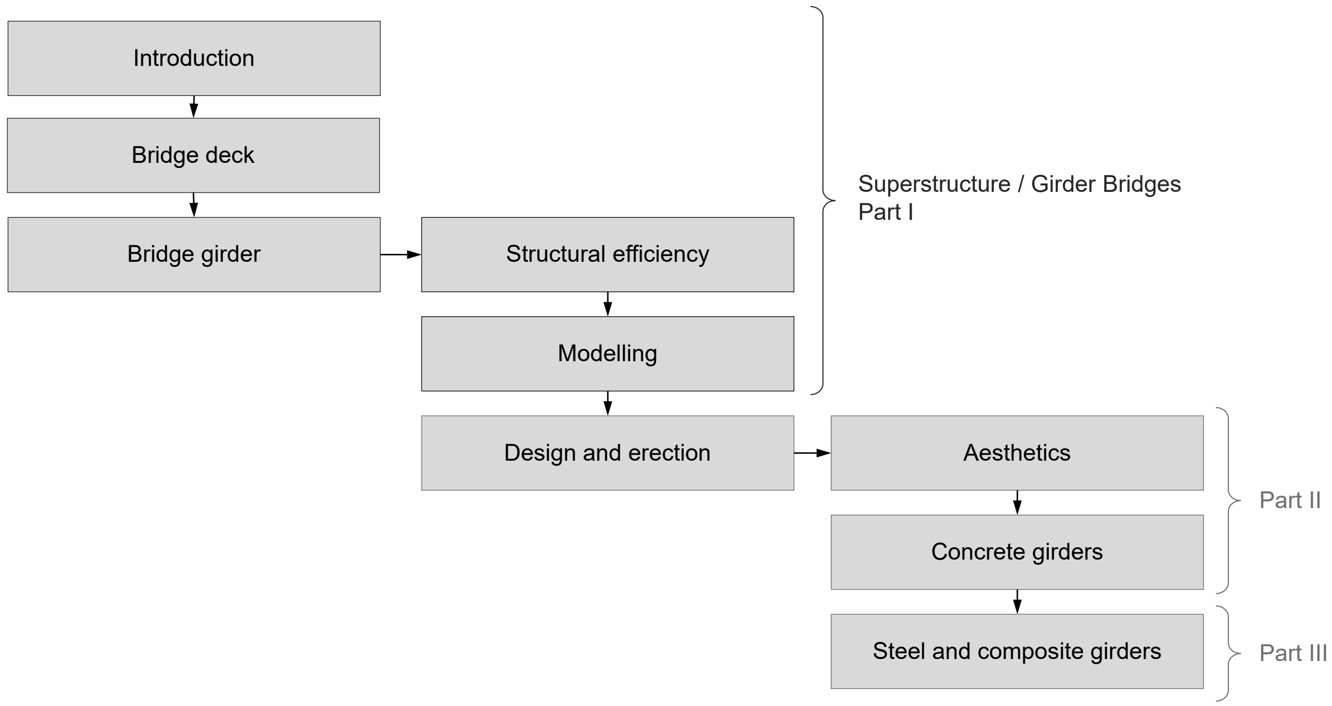
- The soffit of a girder can be rhythmised using transverse ribs or diagonal struts
- This also enhances contrast → higher apparent slenderness
- And at the same time facilitates
  - → wide cantilevers with moderate weight
  - → efficient construction in stages
    1. cast box girder using a narrow launching 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).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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

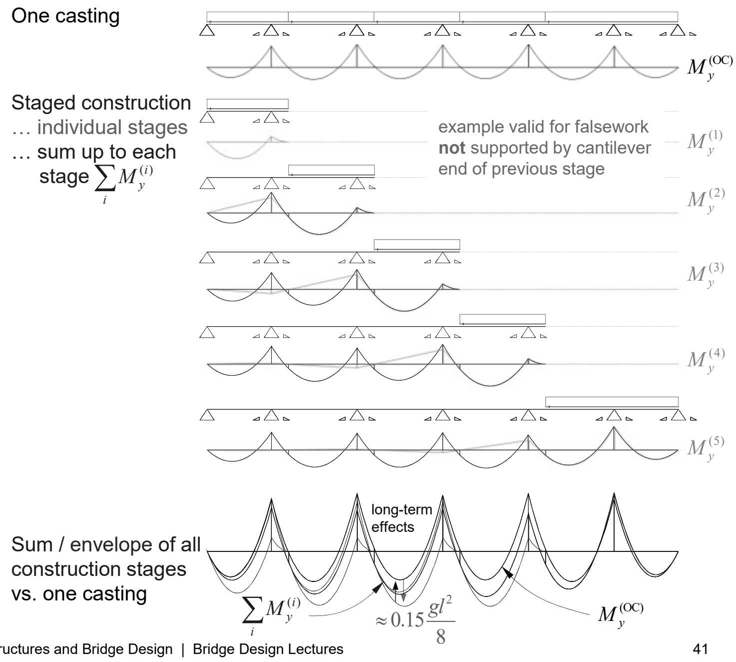
Bottom: Puente sobre el río Narcea, Asturias, Carlos Fernández Casado (2016). © CFCL SL

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)



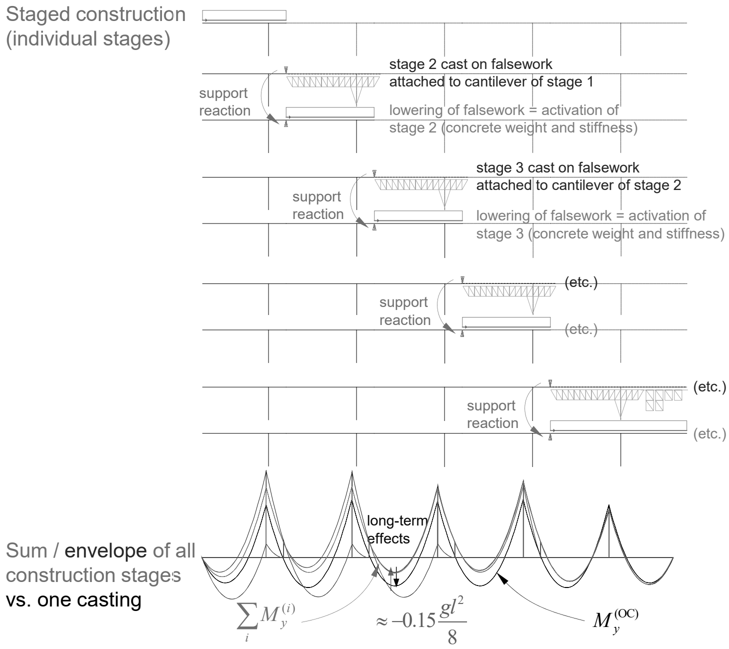
Note that the maximum volume of concrete that can be cast in a single day is in the order of 1'000 cubic meters.

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=∞, 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)

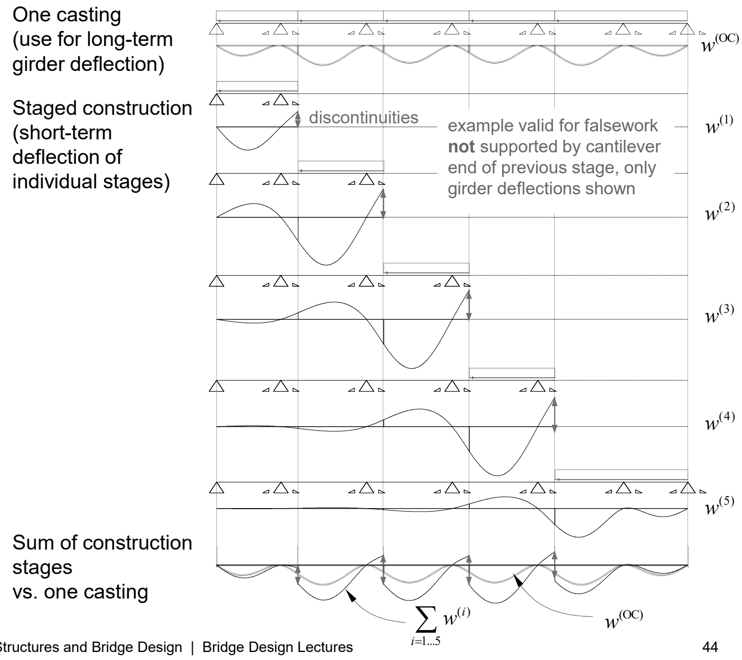
Photos: Innbrücke Vulpera, casting of end span on falsework suspended from cantilevered girder. On request of the contractor, the end span was cast in two stages: (1) U-section, and (2) deck slab, rather than in one casting together as planned. This lead to the problem that the U-section (much stiffer 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)



The sum at the end of the Slide refers to the sum of the deflections of all construction stages per span.

As an example (right side), if simply supported falsework girders are used, they individually deflect (under wet concrete load at casting), plus the height of the girder camber curve’s segment between the falsework girder supports needs to be accounted for. The latter of course need to be set at the level of the camber curve (plus any anticipated settlement of falsework supports).

GSA1

Concrete girders – Structural analysis and design

Bridge-specific aspects of 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

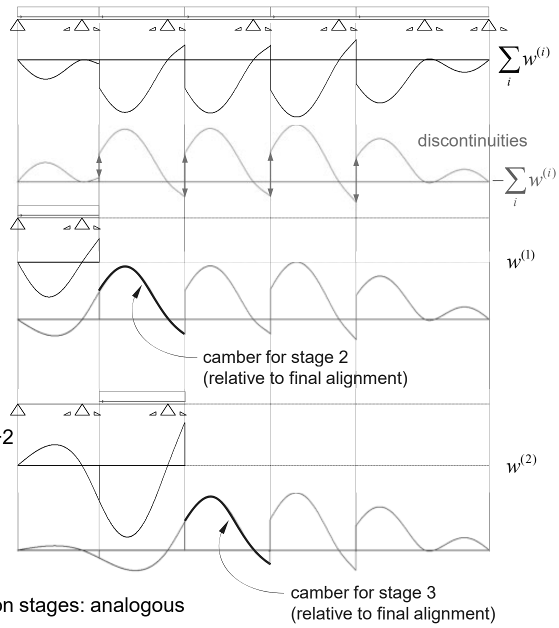
Camber due to staged construction (girder part only, negative of above)

+ 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

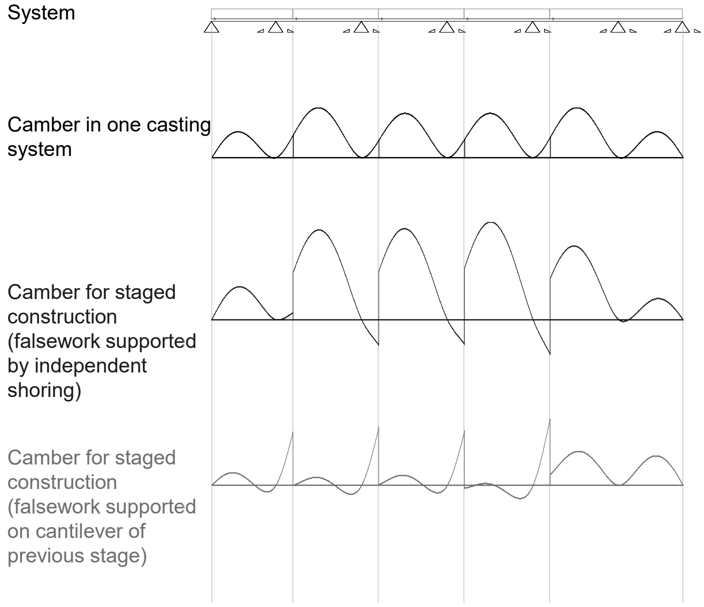
How camber is realised depends on the erection method, particularly on the type of falsework used. As an example, if simply supported falsework girders are used, they have to be individually cambered for their individual deflection (under wet concrete load at casting), plus the height of the girder camber 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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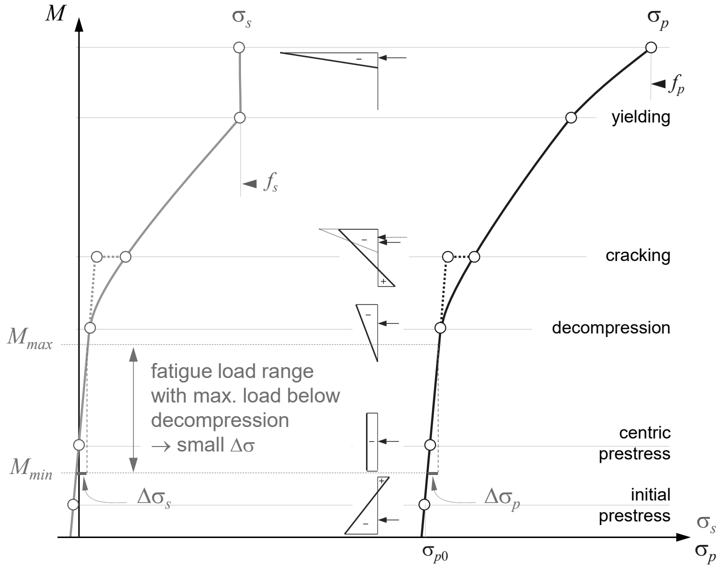
Concrete girders – Structural analysis and design

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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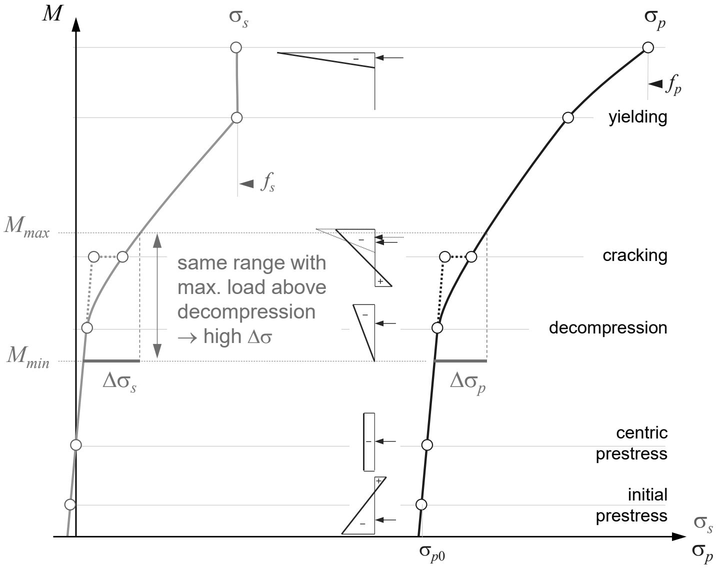


Superstructure / Girder bridges

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

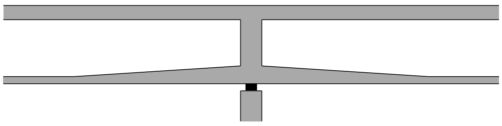
Slab geometry

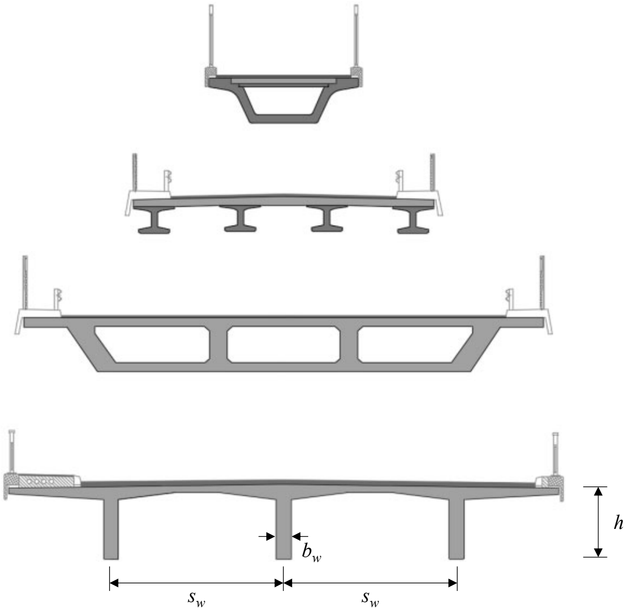
The deck slab and the bottom slab in box girders contribute significantly to the dead load

→ 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!)

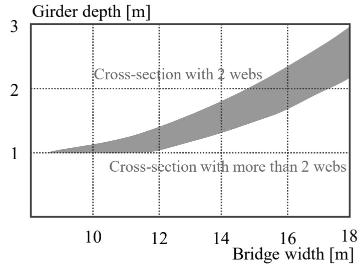
→ reduce number of webs by providing transverse ribs (however: complicated formwork)

→ use transverse prestressing

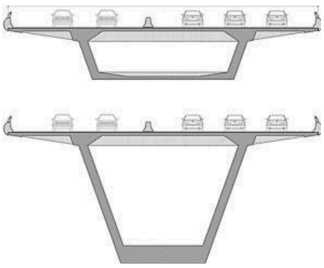
→ reduce web weight (truss webs) in long-span bridges

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.

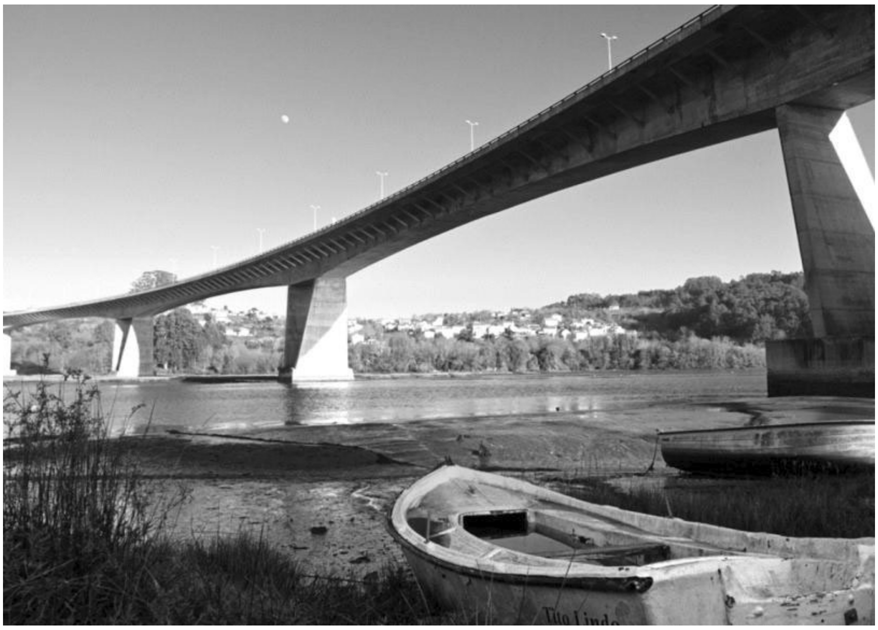
Viaducto de Montabliz, Cantabria, Spain, 2008, Apia XXI Ingenieros, Photo © Ferrovial Agroman

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.

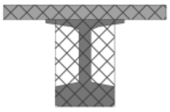


Puente sobre la Ría de Betanzos, La Coruña, ES, Juan José Arenas (1996)

Photo © Arenas y Asociados.

Concrete girders – Typical cross-sections and details

Cast-in-place girders



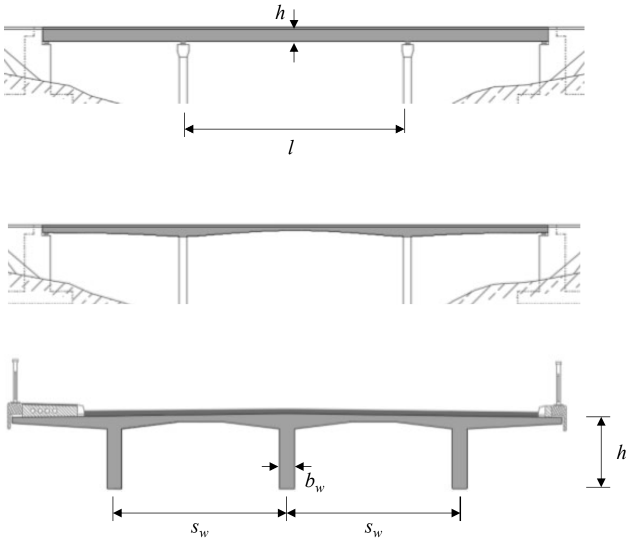
- Simple cross-sectional geometry = formwork and construction is more important than optimising weight. Hence, they are usually

→ 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

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

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

variable depth girder

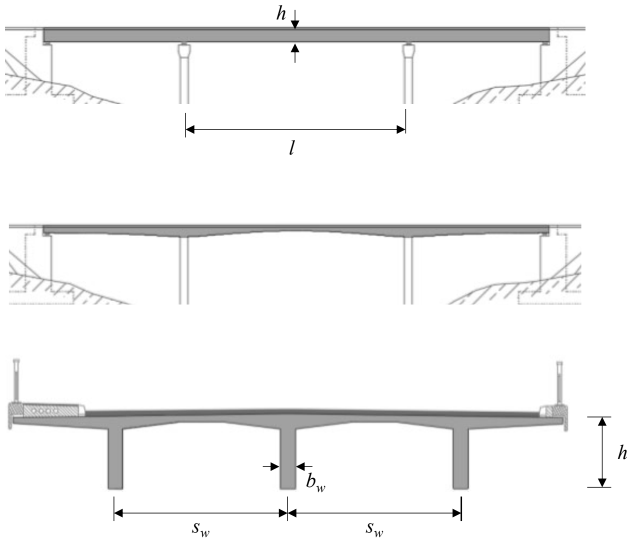
supports $\frac{h}{l} \cong \frac{1}{20}$

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

free cantilevered

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

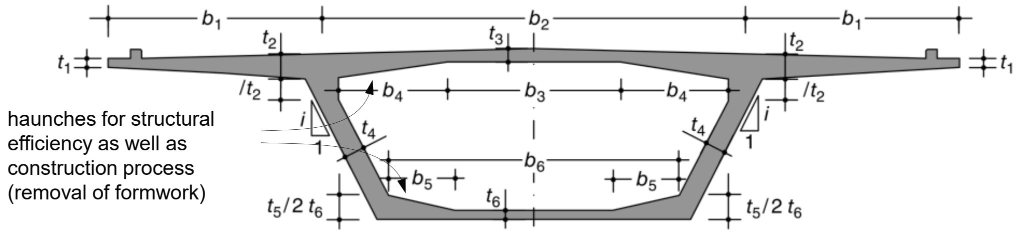
midspan $\frac{h}{l} \cong \frac{1}{50}$



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 ≥ 3…4 …5 (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

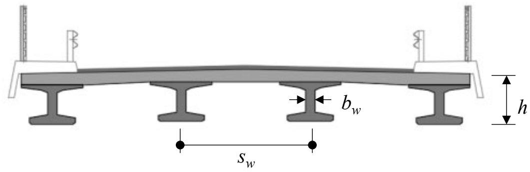
- Complex cross-section geometries and structural optimisation possible (maximise radius of gyration $\sqrt{\frac{I}{A}}$)

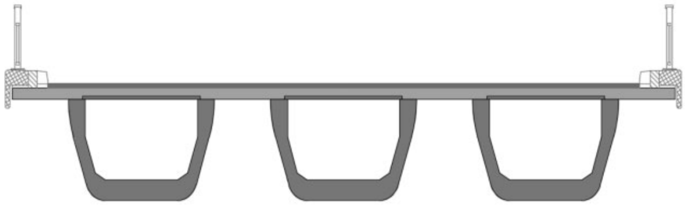
- Construction / erection = positive
  - simple construction
  - fast erection
  - elimination of falsework

- 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



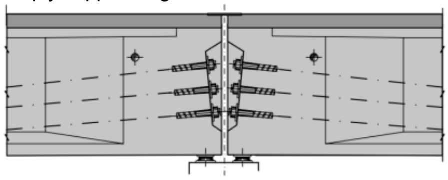


Concrete girders – Typical cross-sections and details

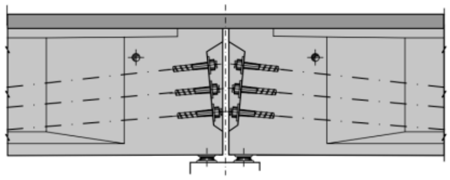
Precast girders – Arrangement over supports

- 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

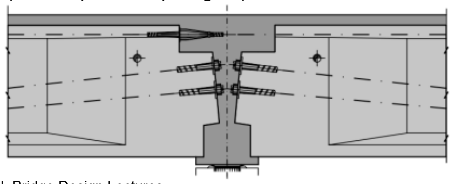
Independent, simply supported girders



Partial continuity (monolithic deck slab)



Full continuity (cast-in-place diaphragms)



Illustrations adapted from Reis Oliveiras, Bridge Design.

KW1

Concrete girders – Typical cross-sections and details

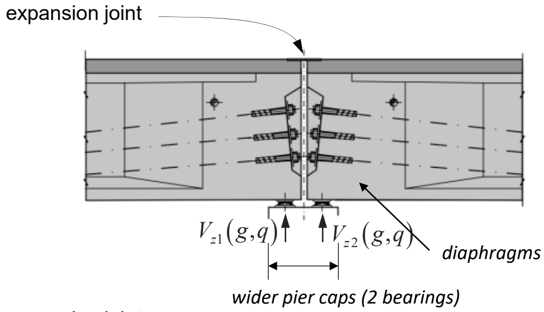
Precast girders – Arrangement over supports

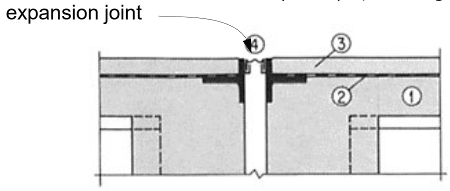
Independent, simply supported girders

- 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.

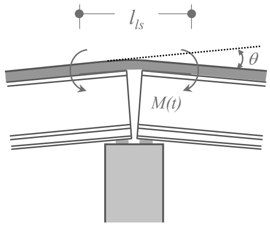
Illustrations: Reis Oliveiras, Bridge Design (top); Ch. Menn, Prestressed Concrete Bridges (bottom)

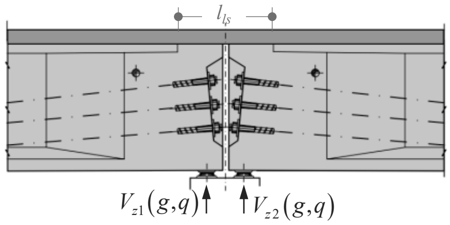
Concrete girders – Typical cross-sections and details

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)

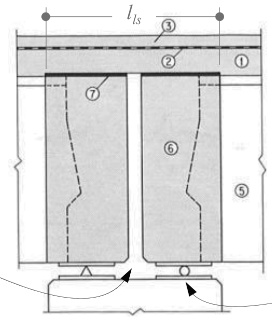




typical length l_{ls} of «link slabs»:

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

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



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)

KW1

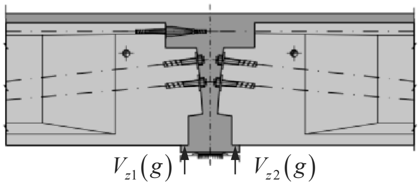
Concrete girders – Typical cross-sections and details

Precast girders – Arrangement over supports

Full continuity (cast-in-place diaphragms)

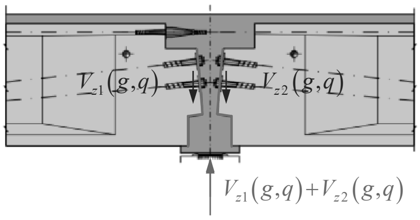
- Erection of simply supported girders
- Pier cap (ev. with auxiliary falsework) must accommodate the temporary supports of both girders as well as the common final support
- Establishment of full continuity through
  … cast-in-place diaphragm and deck
  … continuous prestressing
  → no expansion joints, 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

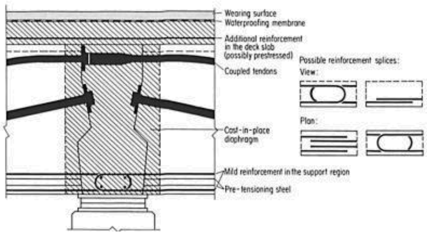


Casting of Diaphragms

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

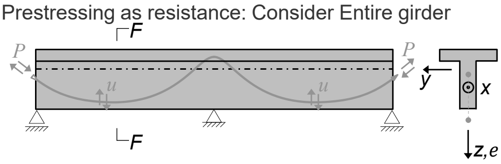
Concrete girders – Prestressing concept

Prestressing concept

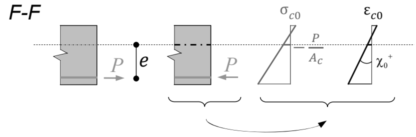
The prestressing concept contains (see Stahlbeton II):
- degree of prestress
- tendon layout (profile, anchorages, …)
- tendon sizing
- stressing sequence (where, when)

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

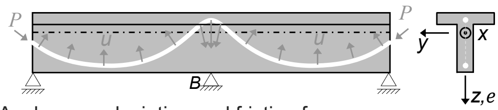
Prestressing as resistance: Consider Entire girder



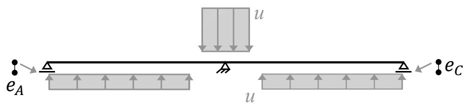
Residual stress state (illustrated at midspan)



Prestressing as load: Girder without tendon



Anchorage, deviation and friction forces:



Concrete girders – Prestressing concept

Degree of prestressing

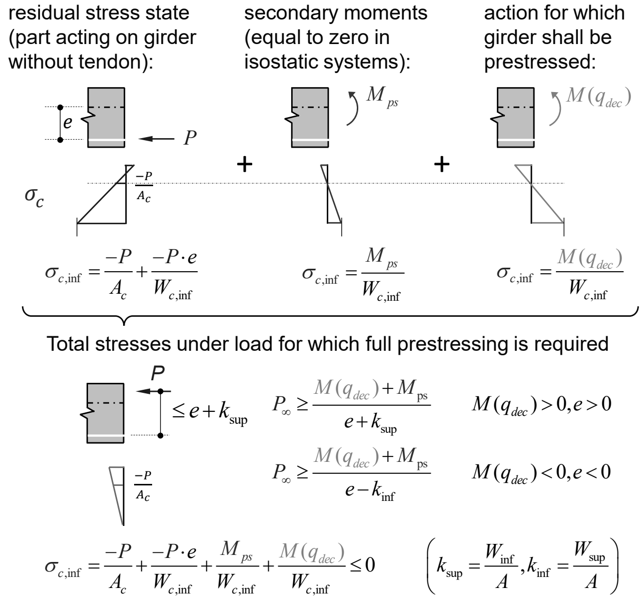
The students are also assumed to be familiar with the concept of the degree of prestressing (Vorspanngrad).

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

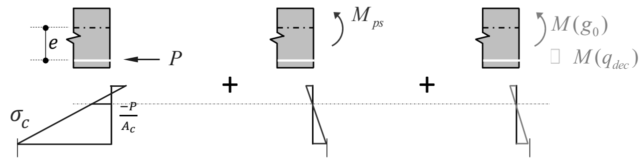
In highly prestressed girders (e.g. railway bridges), decompression may occur under permanent load and prestressing, on the side of the cross-section opposite to the tendons. This is often tolerable in construction stages (reduced dead load q_0), but should usually be avoided in service (full permanent 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

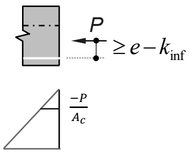
→ strictly speaking, this should be accounted for when determining the strain difference $\Delta\varepsilon$ between girder and tendon (frozen when grouting) – but usually, concrete strains are completely neglected in determining $\Delta\varepsilon$ (see Stahlbeton II)

residual stress state (part acting on girder without tendon): + secondary moments (equal to zero in isostatic systems): + action for which girder shall be prestressed:



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

Total stresses without variable load



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

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

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

Concrete girders – Prestressing concept

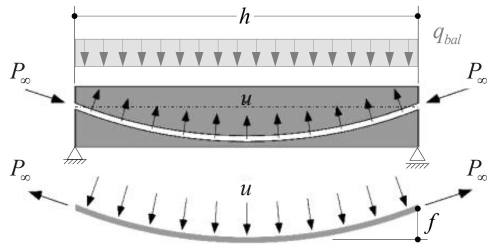
Degree of prestress

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
  $\rightarrow$ 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

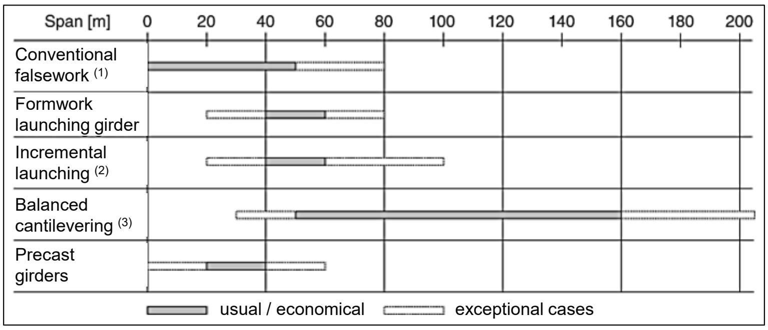
Prestressing concept

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

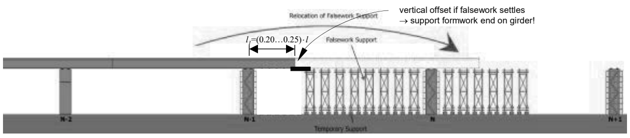


(1) usually most economical cast-in-place solution for low bridges with few spans
(2) requires suitable alignment (straight / circle / helix), economical for long bridges only
(3) economical for high bridges or spans crossing obstacles with restricted access

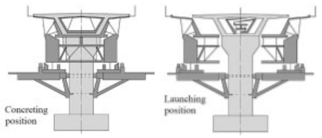
Table adapted from Reis Oliveiras, Bridge Design.

Concrete girders – Cast in place erection methods and prestressing layout

Erection on falsework (conventional falsework)



Movable Scaffold System MSS

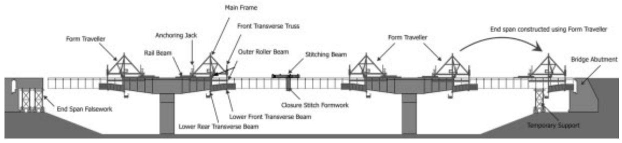


Tendon layouts for cast-in-place girders
(cast on conventional falsework or using MSS)

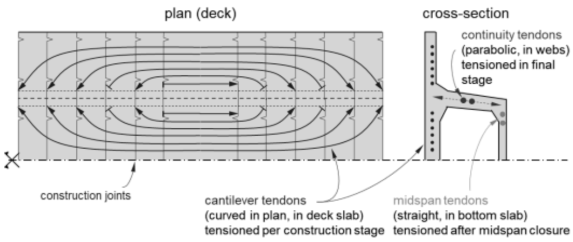
(a) tendon layout with overlap over piers (→ box girders, open cross-sections)

(b) tendon layout without overlap over piers (→ open cross-sections)

Free / balanced cantilevering (*Freivorbau*)



Tendon layouts for balanced cantilevering



More details about cast-in place erection methods and tendon layout can be found in the autography of the lecture notes (or Max Meyer’s guest lecture notes).

For the prestressing layout of balanced cantilevering, 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).

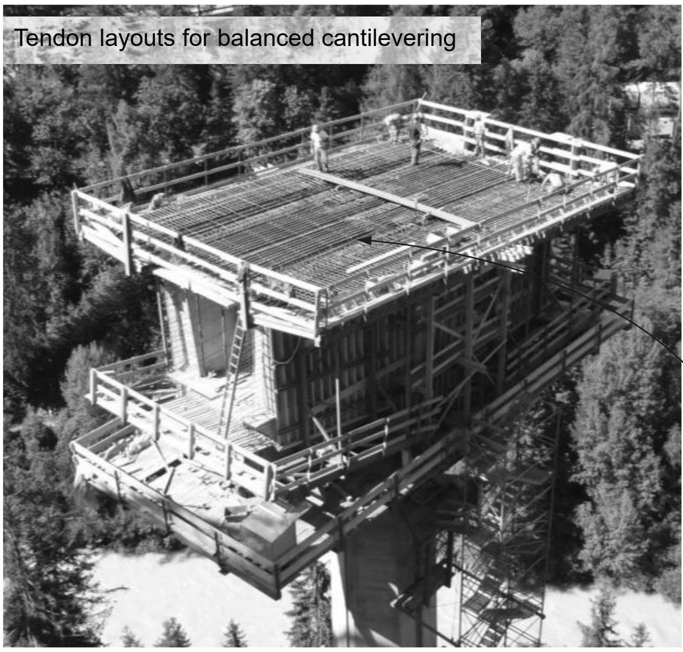
Illustrations construction sequences:

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

Illustration MSS System: Ilustration: T. Siwowski, Bridge Engineering: Selected Issues, 2015

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

Concrete girders – Cast in place erection methods and tendon layout



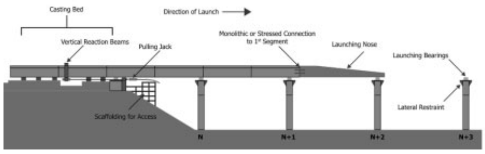
cantilever tendons
(curved in plan, in deck slab)
tensioned per construction stage

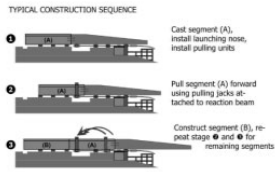
continuity tendons
(parabolic, in webs)
tensioned in final stage

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

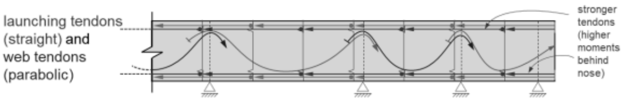
Concrete girders – Precast girder erection methods and prestressing layout

Incremental launching ("precast on site")



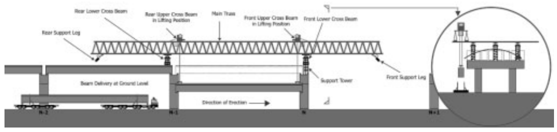


Tendon layouts for incrementally launched girders

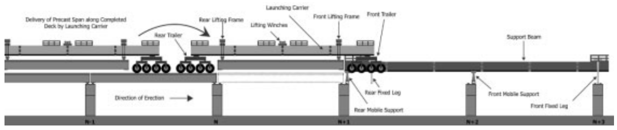


Lifting with cranes

Installation with overhead gantry

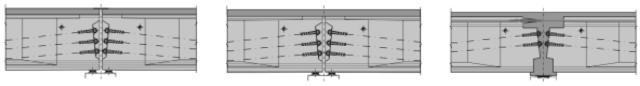


Full span precast method (launching carrier / VSL)



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

Independent, simply supported | Partial continuity | Full continuity



More details about precast girder erection methods and tendon layout can be found in the autography of the lecture notes (or Max Meyer's guest lecture notes).

Illustrations construction sequences:

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

Illustration left (bottom):

Adapted from Reis Oliveiras, Bridge Design.

Photo top right:

Desdoblamiento ctra. C-25 (Espinelves-Santa Coloma de Farnes), Spain © Pacadar SL

Further reading:

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

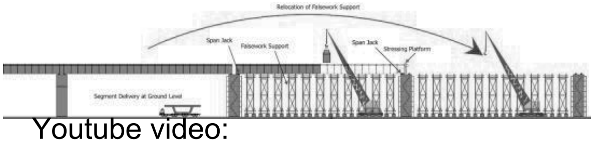
Youtube video:

- https://www.youtube.com/watch?v=S3Kf9e6JgF4

Concrete girders – Precast segment erection methods and tendon layout

Segments are produced in a casting yard by match-casting: Segment n-1 (and a stiff stop formwork) = formwork for Segment n

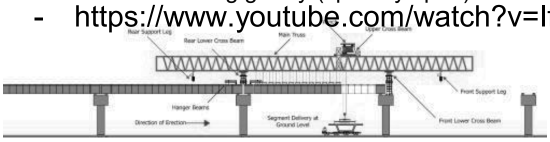
Erection on falsework (span by span)



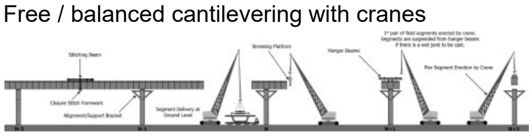
Youtube video:

- https://www.youtube.com/watch?v=If7MS7ygzcY

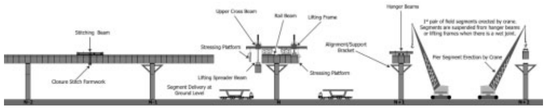
Erection with launching gantry (span by span)



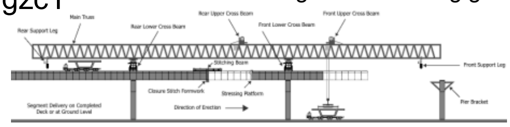
Free / balanced cantilevering with cranes



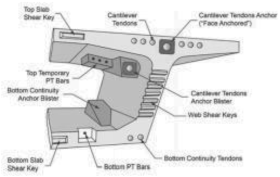
Free / balanced cantilevering with lifting frames



Free / balanced cantilevering with launching gantry



Tendon layout for any precast segment erection method
External prestressing tendons, overlap in pier segments



More details about precast segment erection methods and tendon layout can be found in the autography of the lecture notes (or Max Meyer's guest lecture notes).

Construction sequence illustrations: Adapted from VSL Bridge Erection Brochure, http://www.vsl.com/
Images in bottom right corner:
Left: Segment for cantilevered construction (with internal tendons) © ASBI, see further reading
Right: External tendons inside a segmental box girder © BBR PTE

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.

Youtube video:

- https://www.youtube.com/watch?v=If7MS7ygzcY