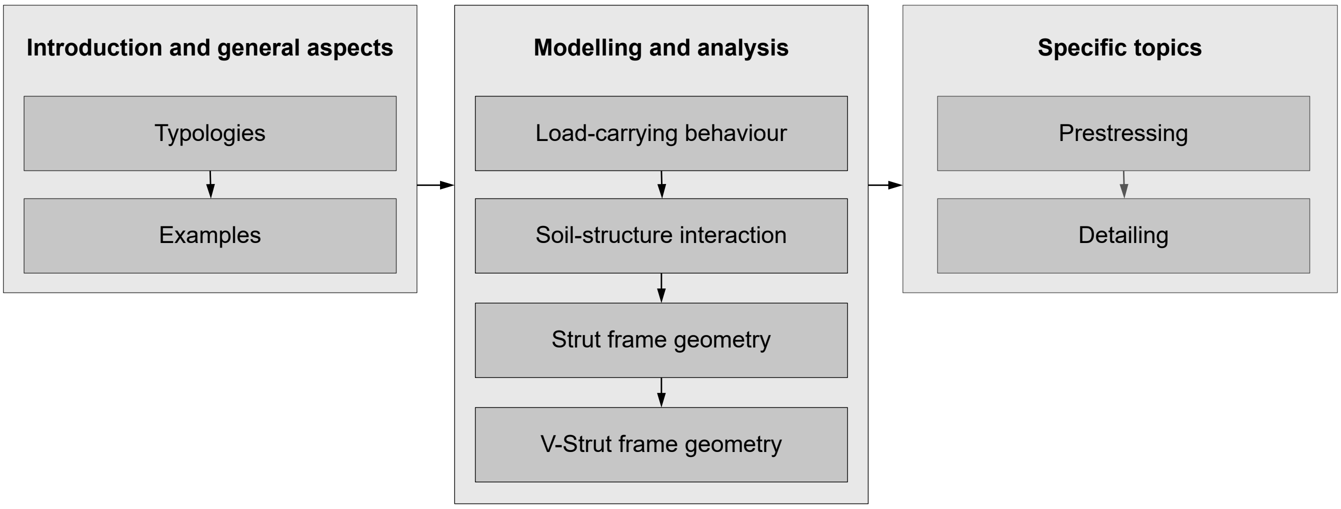
Frame bridges


Introduction and general aspects
Typologies
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Detailing

Frame bridges

Introduction and general aspects

Frame bridges – Introduction and general aspects

Typologies

- Strictly speaking, most bridges are framed structures. While frame action is obviously relevant e.g. in arches and in girder bridges longitudinally stabilised by piers, it also matters in many other cases, where frame action is present in the longitudinal and/or transverse direction of the bridge.
- However, in bridge design, the term “frame bridge” is used only for structures exhibiting pronounced frame action in the transfer of vertical loads, which is similar to that of arches.

Viadotto della Biaschina, Ingenieurbüro Guzzi / Ch. Menn (1983). Length 645 m, spans 58+85+140+160+140+62 m and 78+140+160+140+62 m, width 12.20 / 13.90 m, maximum pier height 100 m. Photo © P. Marti, Ingenieur-Betonbau (O. Monsch)

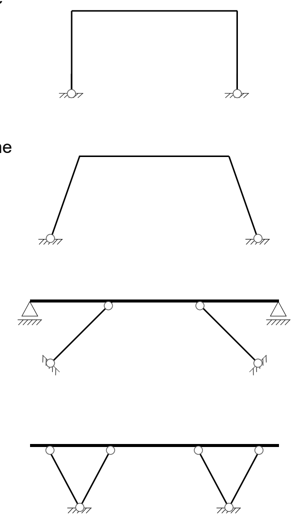
Gateway bridges (Sir Leo Hielscher Bridges), Brisbane, length 1627 m, main span 260 m. VSL (P. Marti / B. Ramsey 1986, duplicated 2011). Photo © https://www.reddit.com/r/bridgeporn/comments/1ag40f/gateway_bridge_at_night_brisbane_australia/

Frame bridges – Introduction and general aspects

Typologies

- Frequent types of frame bridges and their fields of application are illustrated on the right.
- Historically, frame bridges were often idealised to simplify global analysis by introducing hinges. This is still useful in preliminary design, but otherwise obsolete. However, reduced stiffnesses due to cracking (e.g. of the slender V-struts) must be accounted for.
- Frame bridges are often the most economical solution for smaller spans. Orthogonal and trapezoidal frames are particularly suitable for grade separations (flyovers, underpasses – modest structures in many cases).
- Concrete strut frame bridges are more expensive than girder or arch bridges for long spans due to the falsework cost (expensive for inclined piers). Composite bridges, with inclined steel legs, installed from the abutments, are economical for longer spans (see examples behind).

Frame bridge typologies
(and frequently used idealisation = hinges)



orthogonal frame

Constant depth solid cross-section (slab frame): underpasses (e.g. train stations)

Haunched solid or box cross-section: low single-span bridges

trapezoidal frame

Economical for short span buried structures (underpasses)

strut frame
(inclined leg frame)
Sprengwerk

Economical alternative to arch for short and medium spans

V-strut frame
V-Stiel Rahmen

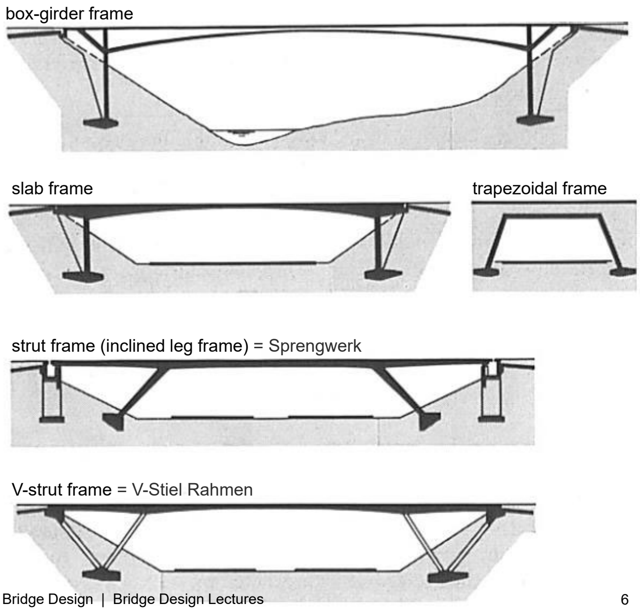
Often used for flyovers in the past

Frame bridges – Introduction and general aspects

Typologies

- Single span frames are particularly suitable for low bridges, since they allow minimising girder depth
  → much higher slenderness possible than for simply supported girders
- The depth of frame bridges at midspan is usually not sufficient for a box girder (access for maintenance)
  → in large span frames, use open cross-section at midspan and add bottom slab = box girder in frame corners (negative bending moment region) required)
- Single span frame bridges are always integral, strut frame bridges and V-strut frames are often integral or semi-integral as well
  → high durability, low maintenance
  → no uplift problems even at pronounced skew (V-strut frame bridge ends may, however, require regular pavement maintenance due to vertical movements of the bridge ends)

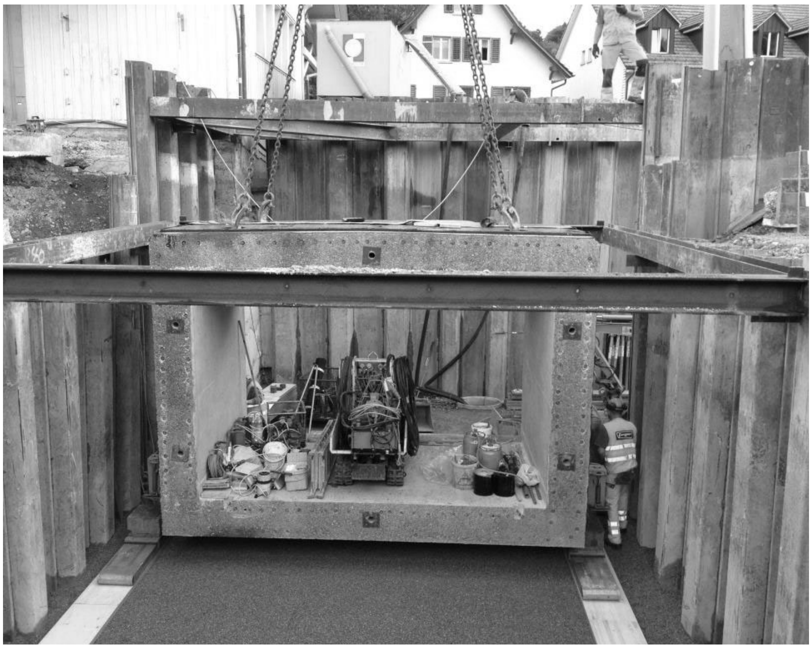
Frame bridge typologies – illustration from Menn (1990)



Frame bridges – Introduction and general aspects

Examples: Train station at Rikon

- Buried orthogonal frame for train station pedestrian underpass (a bridge …)
- Precast elements ("Fanger-Elemente")
- Installation in extremely short time (railway line interrupted)

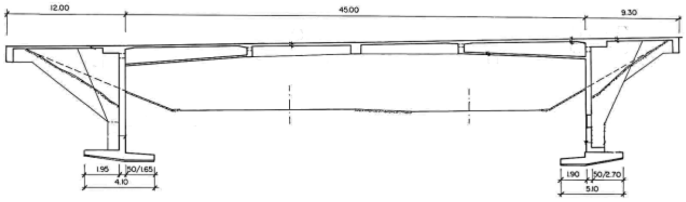


Train station Rikon underpass (2013) © dsp Ingenieure + Planer AG.

Frame bridges – Introduction and general aspects

Examples: Flyover at Widnau

- Slender single span prestressed concrete frame bridge
- Span ca. 45 m, depth at midspan 1.10 m ≈ l / 41
- Extremely complex geometry (variable skew and gradients)



N13 u 9. Überführung Anschluss Widnau, Diepoldsau, Zähner Ingenieurbüro St- Gallen (1960), Slab/TT-girder frame, span ca. 45 m (heavily skewed), h=1.10 m … 2.10 m

Photos and illustration right side: Kaufmann, W. und Buchheister, J. Erfahrungen mit langen integralen Brücken. AGB Report 679, 2014. Left side © Google Street View.

Frame bridges – Introduction and general aspects

Examples: Hofbrücke (Aarebrücke) Innertkirchen

- Slender single span prestressed concrete slab frame,
- Clear span 42 m, length 51.40 m
- Replacing Maillart’s bridge from 1934 to increase hydraulic capacity

Hofbrücke Innertkirchen, Bänziger Partner mit Eduard Imhof (2009), prestressed concrete single span slab frame, span 42 m, length (including frame corners) 51 m

Photos © Eduard Imhof / Bänziger Partner AG

Frame bridges – Introduction and general aspects

Examples: Stägmattabrücke, Lütschental

- Very slender single span prestressed concrete slab frame
- Clear span 38.5 m, length 60 m, depth at midspan 0.80…1.60 m
- Replacing previous bridge destroyed in flood event 2005
- Built using overhead gantry (hydraulic capacity during construction)

Stägmattabrücke Lütschental, Bänziger Partner mit Eduard Imhof (2008), prestressed concrete single span slab frame, span 38.5 m, length (including frame corners) 60 m, h= 0.80…1.60 m, skew crossing

Photos and illustrations © Eduard Imhof

Frame bridges – Introduction and general aspects

Examples: Brücke Schönenwerd

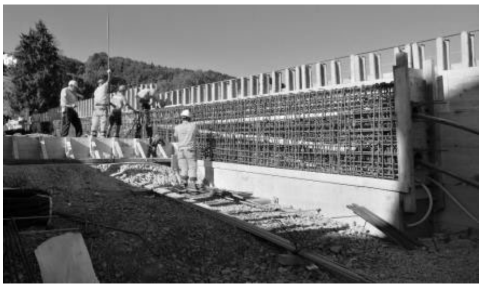
- Single span composite frame bridge with pronounced skew
- Prestressed concrete half-frame with cantilevers supporting the composite part of the span (four weathering steel box girders).

Brücke Schönenwerd, dsp Ingenieure + Planer AG (2018). Span 51 m, variable width (17.3…19.9 m), crossing angle ca. 30° (60° skewed).

Frame bridges – Introduction and general aspects

Examples: Brücke Ruckhalde

- Skewed single span prestressed concrete trough frame bridge
- Minimum depth to cope with clearance requirements (changes in rail track alignment restricted by maximum slope and radius)

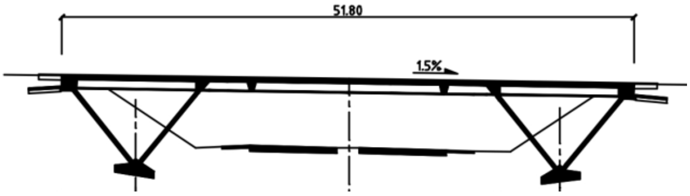


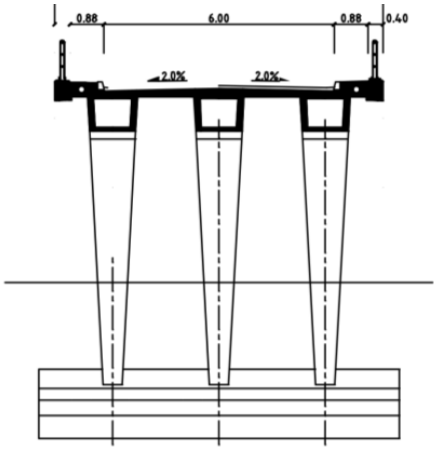
Brücke Oberstrasse (Ruckhalde), dsp Ingenieure + Planer AG (2018). Narrow gauge railway bridge, span ca. 20 m, depth 1.45 m, total length 43 m, crossing angle ca. 60° (30° skewed).

Frame bridges – Introduction and general aspects

Examples: Flyover at Düdingen

- Prefabricated V-strut frame overpass
- Standardised solution in CH, frequently used in motorways built in 1960-70s





Überführung der Verbindungsstrasse Räsch-Wittenbach, Düdingen, Soutter+Schalcher (standard project) (1965), prefabricated V-strut frame, span 38.40 m, length 51.80 m.

Photo and illustrations: Kaufmann, W. und Buchheister, J. Erfahrungen mit langen integralen Brücken. AGB Report 679, 2014.

Frame bridges – Introduction and general aspects

Examples: New Versamertobel Bridge

- prestressed concrete strut frame bridge, cast in situ
- Erected by (i) constructing legs (expensive falsework); (ii) supporting girder falsework on legs; (iii) casting girder

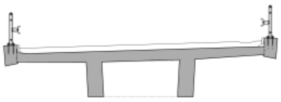
Neue Versamertobelbrücke, dsp Ingenieure+Planer AG (2012). Total length 112.30 m, strut span 80 m, width 8.80 m, >70 m above ground

Frame bridges – Introduction and general aspects

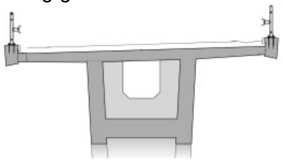
Examples: New Versamertobel Bridge

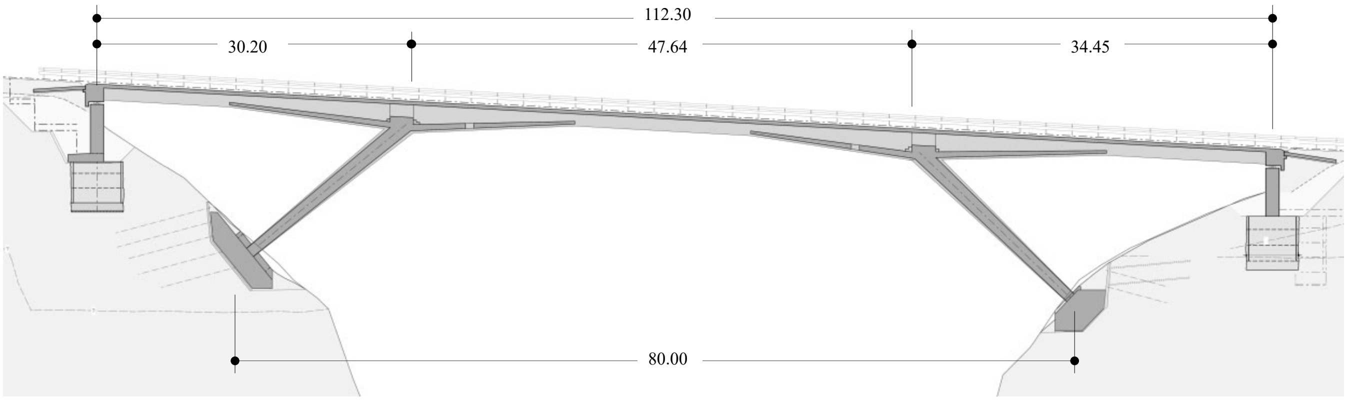
- Concrete strut frame bridge, cast in situ
- Erected by (i) constructing legs (expensive falsework); (ii) supporting girder falsework on legs; (iii) casting girder

midspan



leg-girder connection





Neue Versamertobelbrücke, dsp Ingnieure+Planer AG (2012). Total length 112.30 m, strut span 80 m, width 8.80 m, >70 m above ground

Photos © dsp Ingenieure+Planer AG

Frame bridges – Introduction and general aspects

Examples: Pont de la Dala

- Composite strut frame bridge
- Structurally very efficient system, very slender
- Erected by (i) tilting the legs (built vertically),
  (ii) launching the girder longitudinally on the legs and
  (iii) casting the deck on the girder

Pont de la Dala, Varen-Leuk (1989). Zwahlen&Mayr SA. Length 62.10+85.40+62.10 = 209.6 m, strut span ca. 175 m, 130 m above ground.

Photos © iBeton 1999-2020, O. Burdet.

Frame bridges – Introduction and general aspects

Pont de la Dala, Varen-Leuk (1989). Zwahlen&Mayr SA. Length 62.10+85.40+62.10 = 209.6 m, strut span ca. 175 m, 130 m above ground.

Photo © Björn Sothmann

Frame bridges – Introduction and general aspects

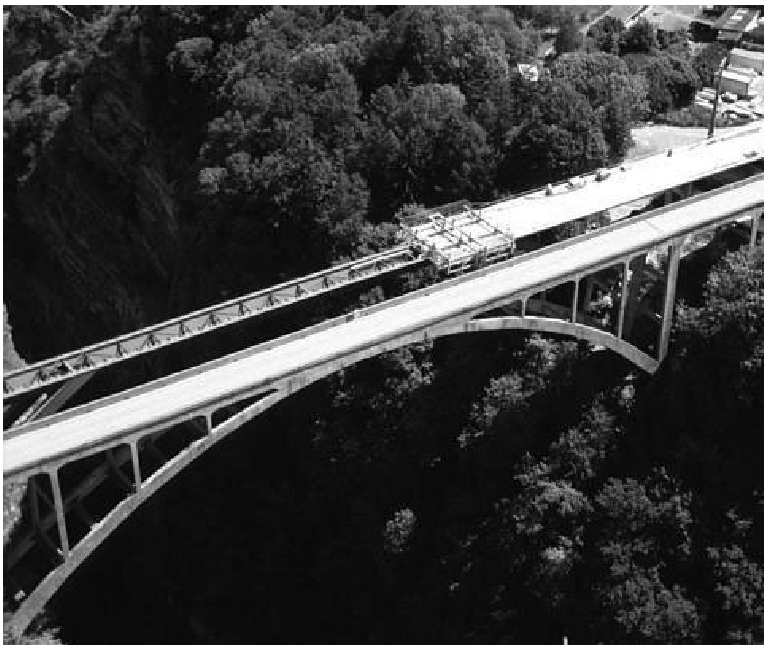
Examples: New Pont du Gueroz

- Composite strut frame bridge
- Structurally very efficient system, very slender
- Erected by (i) tilting the legs (built vertically),
  (ii) launching the girder longitudinally on the legs and (iii) casting the deck on the girder

Nouveau Pont du Gueroz, Vernayaz, (1994). Gianadda+Guglielmetti Ingénieurs, Zwahlen&Mayr SA. Length 170 m, strut span 109 m, 189 m above ground.

Note: Bridge built next to Alexandre Sarrasin’s pont du Gueroz from 1934 (see Eminent Structural Engineers, Alexandre Sarrasin)

Frame bridges – Introduction and general aspects



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Note: Bridge built next to Alexandre Sarrasin’s pont du Gueroz (see Eminent Structural Engineers, Alexandre Sarrasin)

Photos © I Beton 1999-2020, O. Burdet / high resolution http://www.randonnee-pedestre.ch/

Frame bridges – Introduction and general aspects

Nouveau Pont du Gueroz, Vernayaz, (1994). Gianadda+Guglielmetti Ingénieurs, Zwahlen&Mayr SA. Length 170 m, strut span 109 m, 189 m above ground.

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Photo left side © I Beton 1999-2020, O. Burdet / right side © http://www.randonnee-pedestre.ch/

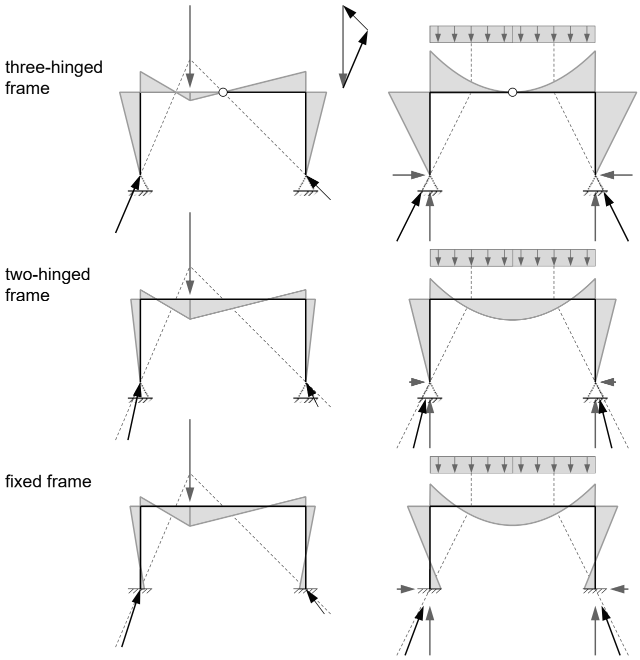
Frame bridges

Modelling and analysis

Frame bridges – Modelling and analysis

Load-carrying behaviour

- Historically, frames were not only analysed, but also built with hinges to avoid restraint due to imposed deformation, settlements etc. Today, hinges are avoided (durability); the three-hinged frame is used here only to illustrate the behaviour (top row figures):
  → pronounced frame action = strongly inclined reactions, large hogging moments at frame corners
- If the legs are haunched, reducing the depth towards the foundation, behaviour is similar to a two-hinged frame (figures in middle row):
  → reduced frame action compared to three-hinged frame (lower hogging moments, less inclined reactions)
- However, frames are usually (partially) fixed at the base (bottom row figures):
  → similar hogging moments as two-hinged frame
  → bending moments in legs change sign
  → higher shear forces in legs than for two-hinged arch (inclination of reactions in-between two- and three-hinged frame)

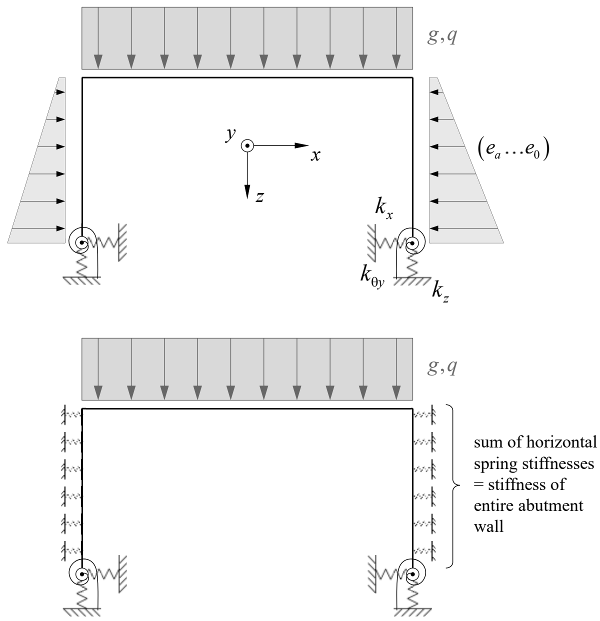


Note that the figure illustrates the behaviour for constant bending stiffness, equal for legs and girder – loads are the same in all three systems, and bending moments plotted to scale.

Frame bridges – Modelling and analysis

Soil-structure interaction

- In reality, frames are typically neither fixed nor hinged at the base, but elastically clamped
  - → behaviour between fixed and two-hinged frame
- Furthermore, the foundations are flexible, particularly in the horizontal direction
  - → frame action significantly reduced in soft soil
  - → model foundation with elastic springs (see substructure)
- In short-span buried frames (underpasses), the backfill is often modelled as load (top figure).
- In abutment walls acting as legs of large span frames, the backfill can be modelled as follows:
  - → apply permanent earth pressure as load (top figure)
  - → model backfill using elastic springs for all other loads (bottom figure)
  - → check that no tension results and passive pressure is not exceeded (relevant value = combination of both models)



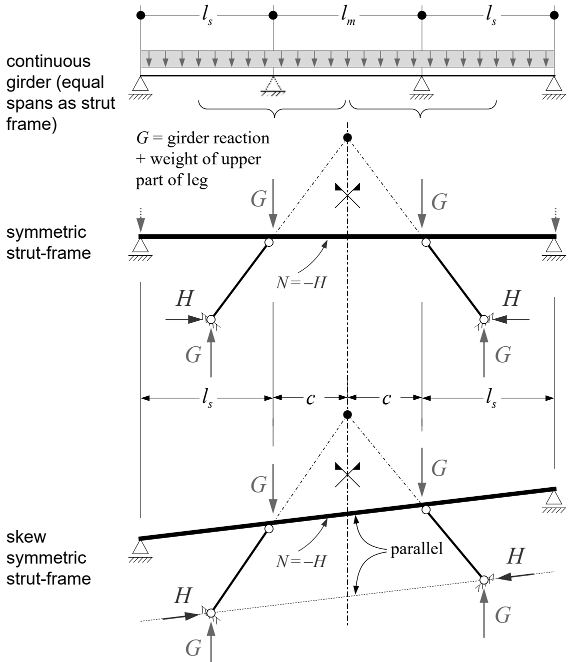
Note that in long span frames, earth pressure may have to be increased due to strain ratcheting, see support and articulation / integral bridges.

The stiffness of the horizontal springs modelling the backfill must be determined accounting for the size of the entire abutment wall, i.e. distributing the stiffness of the entire wall among the springs (adding up elastic springs corresponding to the small areas of each individual spring would severely overestimate the stiffness).

Frame bridges – Modelling and analysis

Strut frame geometry – symmetric and skew symmetric case

- In strut frames, the geometry (leg inclination, girder spans) should be anti-funicular, i.e., correspond to the thrust line of the dead load (girder + upper part of legs):
  - → bending moments in girder ≈ continuous girder
  - → "zero" girder deflection at inclined pier connection (except axial deformation of legs)
  - → no horizontal movements under dead load
- Aesthetically, the connection line of the leg foundations, resp. the leg intersection with the ground, should (as the springing line of arches) be parallel to the girder
- In either case, graphic statics is useful to understand the response and determine the geometry (considering the legs as pin-jointed members)
  - → equal horizontal component of leg forces by equilibrium
  - → equal vertical support reaction = equal leg inclination
  - → slightly different leg inclination in skew symmetric case

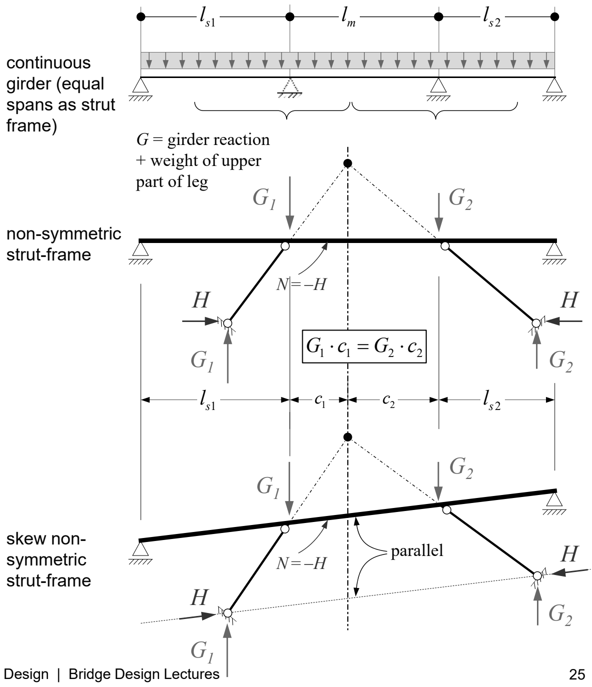


Note that the skew symmetric illustration strictly applies for end supports supported perpendicularly to girder axis; since end reactions and slopes are small, differences in case of vertical end supports are however small.

Frame bridges – Modelling and analysis

Strut frame geometry – non-symmetric case

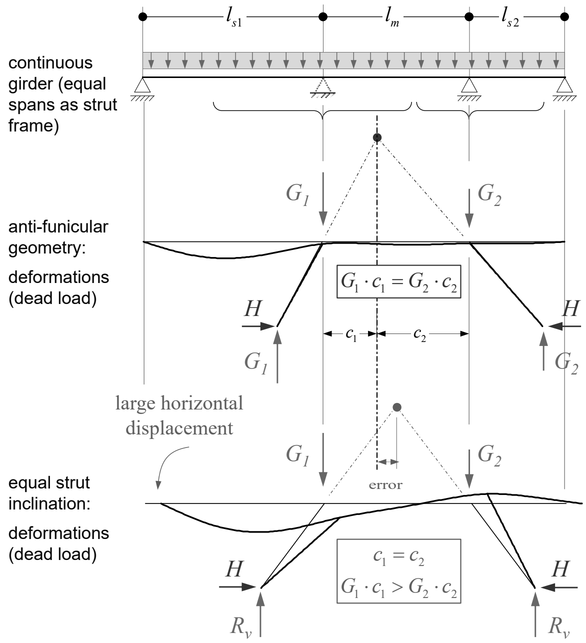
- In non-symmetrical strut frames, choosing an anti-funicular geometry is more important than in symmetric cases, where “symmetric” deviations of the geometry merely cause changes in bending moments, see next slide
- Graphic statics is particularly useful to define the right geometry:
  (i) choose girder span layout ($\rightarrow c_1+c_2$ given)
  (ii) determine support reactions in continuous girder
  (iii) select first leg foundation = inclination $\rightarrow$ inclination of other leg and position of foundation follow from $G_1 \cdot c_1 + G_2 \cdot c_2$
  (iv) iterate until second leg foundation matches topography and layout is aesthetically satisfactory



Frame bridges – Modelling and analysis

Strut frame geometry – non-symmetric case

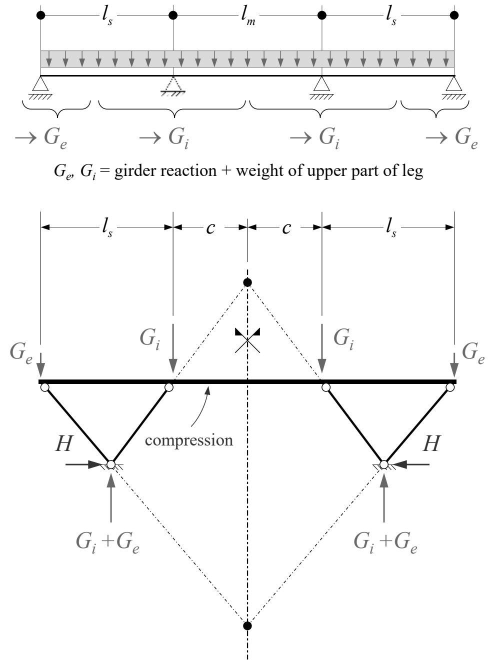
- If the geometry of the struts is not anti-funicular in non-symmetric strut frames (lower figure)
  - → large horizontal displacements under dead load
  - → large girder deflection at inclined pier connections
  - → bending moments in girder ≠ continuous girder (sagging moment in large end span, already critical in anti-funicular case, increases)
- The behaviour can be explained by observing that equal strut inclinations cause equal strut forces (due to horizontal equilibrium), i.e., the vertical component *R* (equal for both legs) is
  - smaller than G_1 (left leg to girder connection)
  - larger than G_2 (right leg to girder connection)
  - → differences between vertical component of leg forces and (G_1, G_2) must be carried by the girder in bending



Frame bridges – Modelling and analysis

V-strut frame geometry – symmetric case

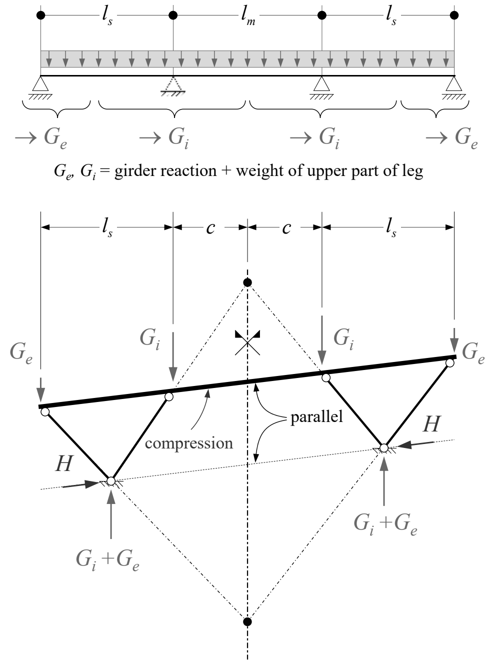
- Similar observations apply to the geometry of V-strut frames, in both the symmetrical case (figures on this and next slide) and non-symmetrical case.
- Depending on the span arrangement and the foundation stiffness (model with horizontal spring), uplift reactions occur at the end supports
  - → rear legs in tension
  - → frequent case in motorway flyovers (main span maximised / side spans minimised)
  - → prestressed legs are a frequent case of damage (improper grouting, see next slides)
- V-strut legs are often embedded in the backfill / embankment
  - → protect V-struts from earth pressure (half tube / soft layer above legs before backfilling)



Frame bridges – Modelling and analysis

V-strut frame geometry – skew symmetric case

- As in strut frames, it is aesthetically favourable if the connection line of the leg foundations, resp. the leg intersection with the ground, is parallel to the girder.



Frame bridges

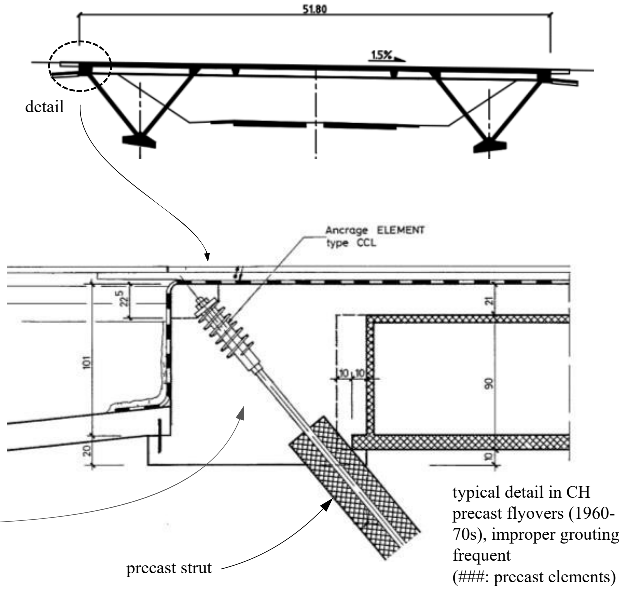
Prestressing

Frame bridges – Prestressing

Prestressing concept and tendon geometry: (V)-strut frames

- Strut frame and V-Strut frame girders can be prestressed as conventional bridge girders, accounting for the fact that
  - → in both cases, the midspan section of the girder is compressed by the frame action (beneficial)
  - → in V-strut frames, the side spans OF THE GIRDER (above each V) are subjected to tension, which requires additional prestressing

- Depending on the span layout and support stiffness (model with springs), the rear legs of V-strut frames are often subject to tension, at least under traffic loads at midspan
  - → prestress rear legs
  - → proper grouting essential for durability
  - → upper end of struts is difficult to grout: use re-/post-grouting (nachinjizierbare Spannglieder)



Überführung der Verbindungsstrasse Räsch-Wittenbach, Düdingen, Soutter+Schalcher (standard project) (1965), prefabricated V-strut frame, span 38.40 m, length 51.80 m.

Illustrations: Kaufmann, W. und Buchheister, J. Erfahrungen mit langen integralen Brücken. AGB Report 679, 2014.

Frame bridges – Prestressing

Prestressing concept and tendon geometry: Single span frames

- Single span frames should at least be fully prestressed for permanent load (no decompression under permanent load).
- Large span, slender single span frames are sensitive to deflections and moment redistributions due to
  - long-term effects (prestressing force losses)
  - horizontal deformations of foundations

  → provide strong prestressing, preferably fully balancing the permanent loads ("formtreue Vorspannung") to ensure concentric compression at $t = \infty$ under permanent load and accounting for foundation flexibility

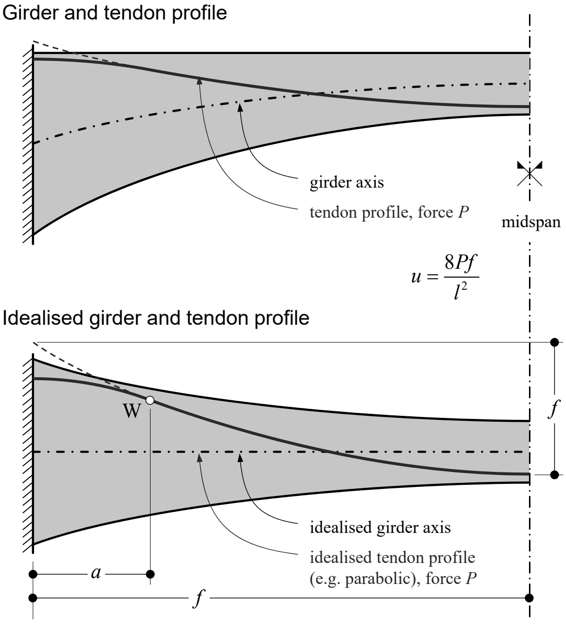
- Deviation forces in variable depth girders may be estimated as illustrated in the figure
- "Parabolic" tendon geometry can be defined using this approach as well

  → define geometry in equivalent girder with horizontal axis

  → transfer eccentricities with respect to real geometry

  (method is applicable in any variable depth girder, e.g. for continuity tendons in cantilever-constructed girders)

Girder and tendon profile



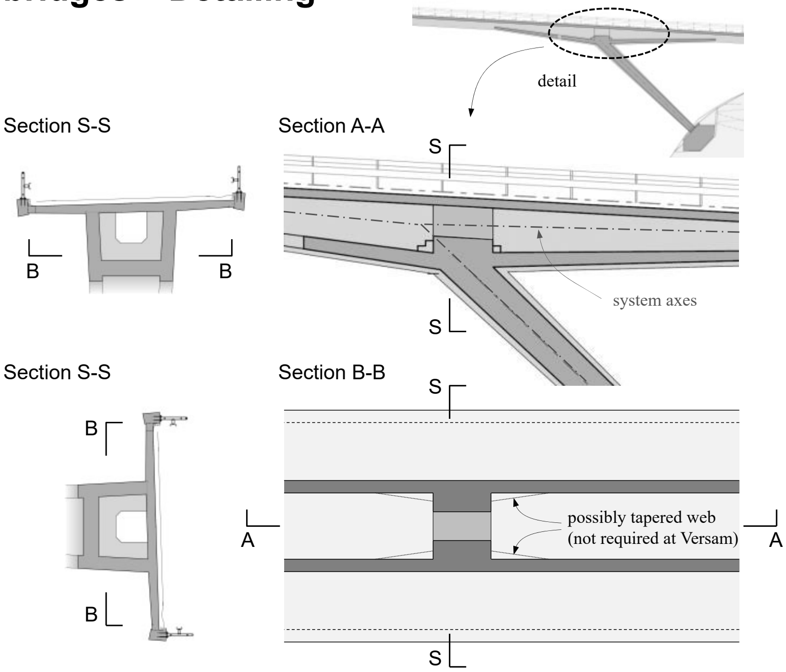
Frame bridges

Detailing

Frame bridges – Detailing

(V-) Strut frame bridges: Strut-girder connection

- Vertical diaphragms are commonly used at the connection of the inclined piers to the girder
- In box girders, provide passage for inspection
- Ensure force flow
  → include moment transfer (even if piers are modelled as pin-jointed members, they transfer bending moments)
  → use strut-and-tie model for detailing (internal actions referred to system axes yield only limited insight in local force transfer)



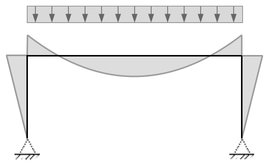
Example: Neue Versamertobelbrücke, dsp Ingnieure+Planer AG (2012).

Frame bridges – Detailing

Single span frames: Abutment walls

- Due to the flexibility of the foundations, bending moments in the piers = abutment walls of single span frames typically decrease strongly towards the base (behaviour close to two-hinged frame)
  → taper abutment walls towards the base
  → often, abutment walls are provided with variable depth ribs
- Abutment walls can usually be provided with sufficient depth
  → no prestressing of walls, even if girder is prestressed (otherwise, detailing is demanding)
- In slab frames (slab and walls as solid slabs, economical up to ca. 15 m span), design is straightforward (2D problem)
- If the abutment wall is provided with ribs, the compressive forces in the slab between ribs need to be transferred (→ small rib spacing, solid section at top of abutment), similar as in a box girder frame (next slide)

bending moments in two-hinged frame



slab frame

solid slab, abutment walls with ribs

prestressed slab, abutment walls with ribs

Frame bridges – Detailing

Single span frames: Frame corners

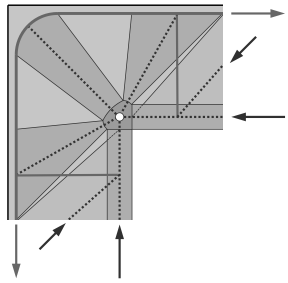
- The frame corners are subject to closing moments
  → much less critical than opening moments, see lecture Advanced Structural Concrete)
  → use strut-and-tie models and stress fields for a consistent dimensioning and detailing (figure)

- Similarly, in box girder frames, a diagonal compression slab is usually required (figure)

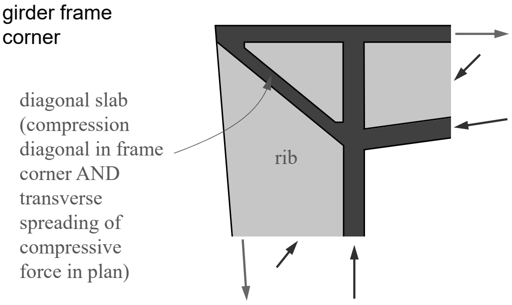
- Skew frames rotate in plan (see chapter on skew bridges)

force flow in slab frame corner

(simplified, for equal depth of wall and slab)



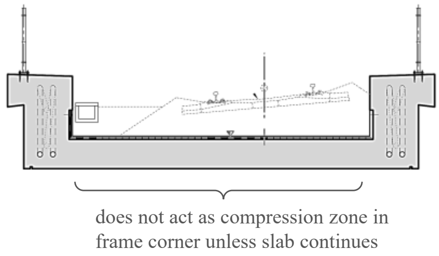
force flow in box girder frame corner

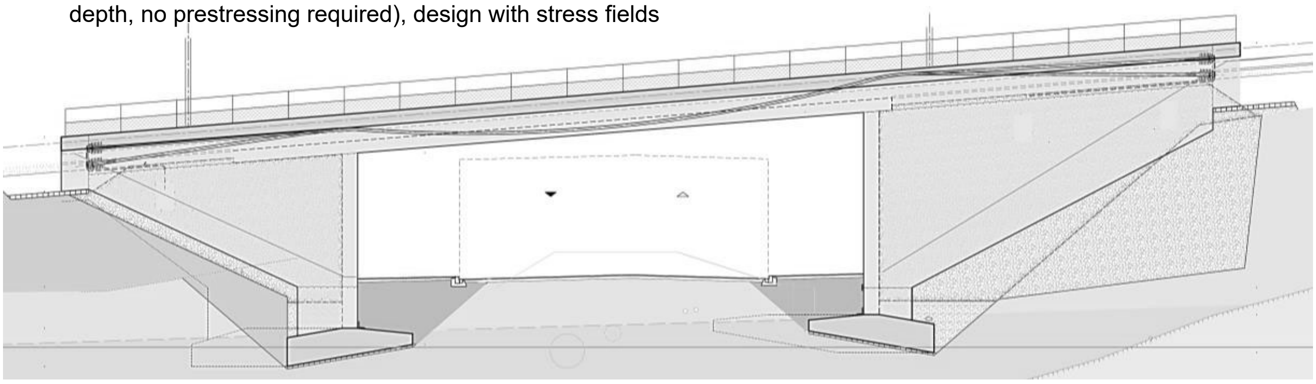


Frame bridges – Detailing

Particularities of trough frames

- Trough frames are appropriate in situations with very limited available depth (due to clearance and alignment requirements)
- In their design, it must be observed that the trough slab cannot be activated in compression in the frame corner, unless a continuing slab providing load spreading is provided (abutment wall cannot resist this high force in transverse shear)
- In turn, the wing walls can be activated for moment transfer (larger depth, no prestressing required), design with stress fields





Brücke Oberstrasse (Ruckhalde), dsp Ingenieure + Planer AG (2018). Narrow gauge railway bridge, span ca. 20 m, depth 1.45 m, total length 43 m, crossing angle ca. 60° (30° skewed).

Frame bridges – Prestressing and detailing