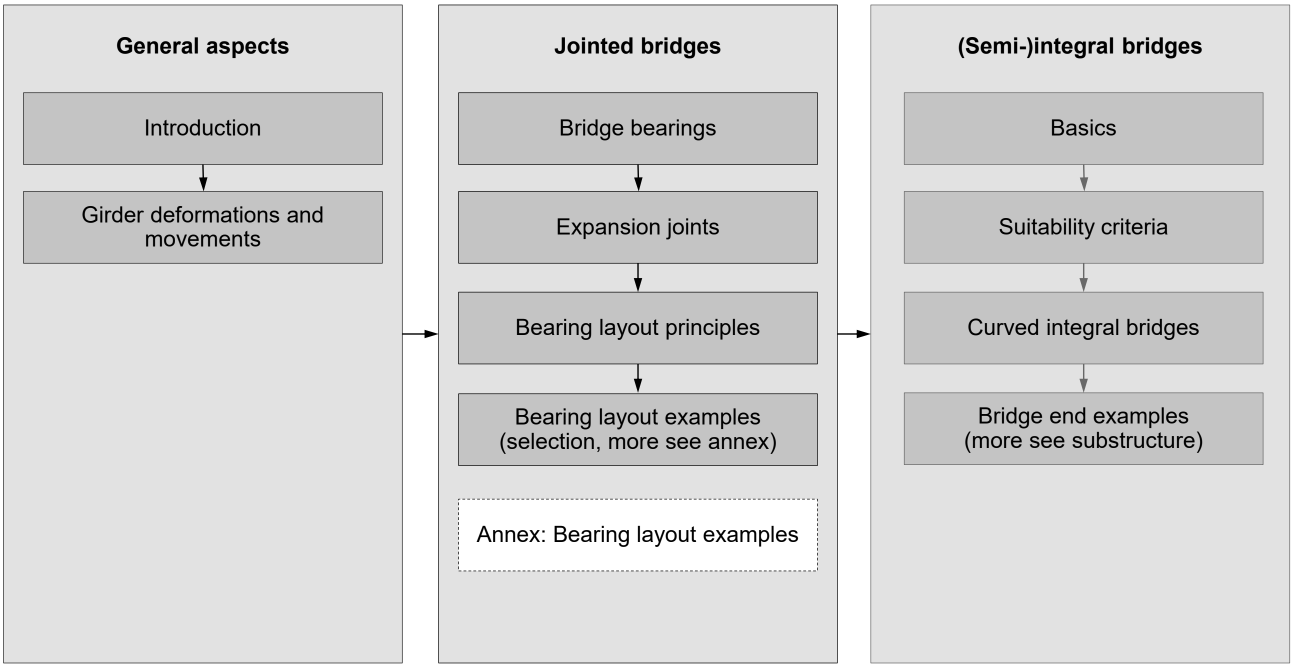
Support and articulation

(Lagerung und Dilatation)



General aspects

- Introduction
- Girder deformations and movements

Jointed bridges

- Bridge bearings
- Expansion joints
- Bearing layout principles
- Bearing layout examples (selection, more see annex)

Annex: Bearing layout examples

(Semi-)integral bridges

- Basics
- Suitability criteria
- Curved integral bridges
- Bridge end examples (more see substructure)

Support and articulation

Introduction

Support and articulation – Introduction

Usually, a bridge consists of a

- superstructure (deck, girder) that is supported by the
- substructure (abutments, piers, foundations)

The connection of superstructure and substructure can be

- monolithic or
- articulated using bridge bearings and expansion joints

The analysis of super- and substructure cannot be completely separated (particularly in the transverse direction), even if articulated connections are provided.

Monolithic connections:

- transfer vertical and horizontal loads as well as bending moments (generally all six stress resultants of a linear member)
- impede the corresponding movements and rotations of the superstructure
- are to be used where possible, rather than providing bearings and expansion joints (reasons see following slides)

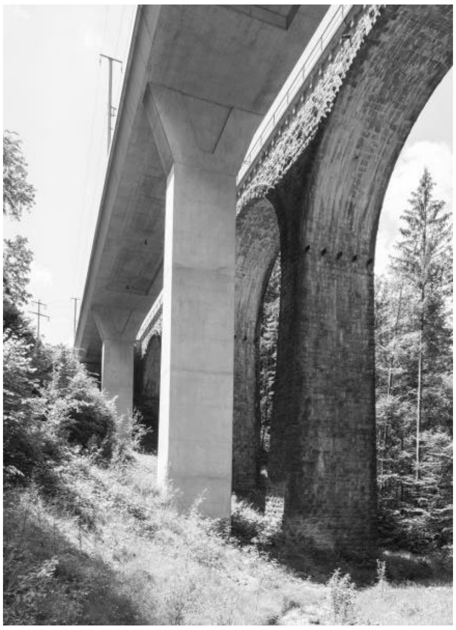


Photo: Old and New Kirchtobelviadukt (monolithic connection of pier to girder), Schweizerische Südostbahn SOB © dsp Ingenieure+Planer

Support and articulation – Introduction

The terms “superstructure” and “substructure” are also usual in other typologies, where the super- and substructure include further components, for example:

Arch bridges

→ superstructure = deck, girder, spandrel columns and arch

→ substructure = abutments, arch abutments, foundations

Cable-stayed bridges

→ superstructure = deck, girder, stay-cables (ev. pylon: see notes & photo on next slide)

→ substructure = abutments, piers, foundations, backstay anchorage, and pylon

Super- and substructure cannot always be clearly distinguished (which is merely a linguistic problem, analysis is coupled anyways):

- arch bridges with bearings on top of spandrel columns:
  … deck and girder alone are often referred to as “superstructure”
- strut frame bridges (photo):
  … struts = superstructure (“arch”) or substructure (“inclined pier”)
- frame bridges / girder bridges with integral abutments:
  … abutment walls = super- and substructure at the same time

Photo: Versamertobelbrücke © dsp Ingenieure+Planer

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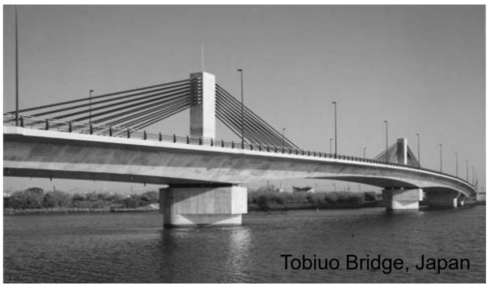


Tobiuo Bridge, Japan

KST Flyover, Poland

Photos:

Tobiuo Bridge - https://www.dywidag-formties.com/projects/2005-info-13/tobiuo-bridge-japan/

KST Flyover - https://www.researchgate.net/figure/View-of-the-KST-flyover-in-cracow_fig4_312265403

Note: The pylons of cable-supported structures are normally considered a substructure element, as they support the superstructure through the cables. In some cases (e.g. extradosed bridges), the pylons are discontinuous along their height: the upper part of the pylon is monolithic with the girder and the lower part of the pylon supports the upper pylon-cables-girder system through bearings. In this case the upper pylon can be considered as part of the superstructure.

Support and articulation – Introduction

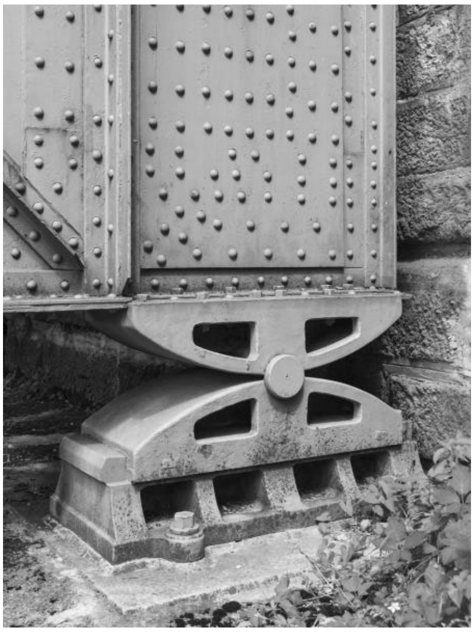
Bridge bearings provide articulation; usually they

- transfer vertical loads and hence impede vertical movements of the superstructure (= provide support)
- enable rotations of the superstructure and hence do not transfer significant bending moments
  (if required, rotational fixity is usually provided by two separate bearings whose reactions generate a force couple, e.g. two vertical bearings resisting torsion)

Bridge bearings may be horizontally fixed or movable in one or both directions. In the corresponding direction(s):

- fixed bearings transfer forces and impede movements of the superstructure
- movable bearings enable movements of the superstructure without significant restraint (friction only)

Often, horizontal fixity is referred to the longitudinal and transverse (lateral) direction. This is suitable in most cases, particularly straight bridges, but may not be useful in curved bridges.



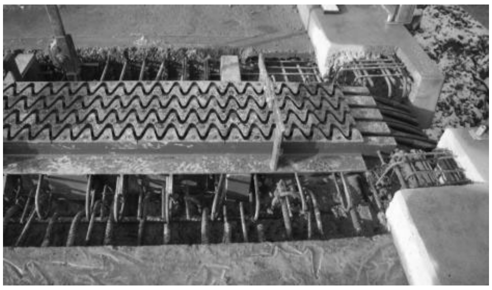
Thurbrücke Ossingen, pin bearing. Photo © Georg Aerni

Support and articulation – Introduction

Bridge expansion joints ensure the serviceability and user comfort at girder ends by accommodating

- relative displacements
- relative rotations

between a bridge girder and the adjoining road or railway track, or between parts of a bridge separated by joints.



Note: Usual expansion joints can accommodate only small vertical relative movements. Further information see section on expansion joints.

Top photo: Finger joint of road bridge (Teufelsschluchtbrücke N2/X11, Kanton Solothurn)
© W. Kaufmann

Bottom photo: Modular expansion joint of Steinbachviadukt (road bridge), with four sealing profiles, provided with noise absorbing sinusoidal plates (total movement capacity 400 mm)
© dsp Ingenieure+Planer AG

Support and articulation – Introduction

For centuries, stone and timber bridges were built without bearings nor expansion joints.

These bridges were able to cope with expansion and contraction caused by temperature and humidity (timber)

- by change of shape (e.g. high arches absorbing contraction by increase in rise)
- a multitude of small joints opening and closing
- lower material stiffness

Photos: Acueducto de Segovia © Tourist office of Segovia / Rhein bridge Stein (CH) – Säckingen (D) © http://bilder4.n-tv.de/img/incoming/origs13972771/017273289-w1000-h960/3m143228.jpg

Support and articulation – Introduction

Modern high strength materials, such cast iron and later steel and reinforced concrete, enabled

- more slender structures
- long, jointless girder bridges with a very high axial stiffness

→ restraining the expansion and contraction of such girders
… generates restraint stresses
… but completely impeding expansion and contraction would require huge forces that usual abutments cannot resist

→ expansion and contraction of the bridge girder
… usually cannot be avoided
… may cause damage to abutments that are not designed to absorb these movements

Damage due to expansion and contraction was e.g. observed in the abutments of early iron bridges that, unlike the ones shown to the right, were connected to masonry abutments without bearings (reportedly e.g. in the Pont des Arts in Paris, 1803).

The Rheinbrücke Eglisau shown on the slide (and similar bridges, e.g. Sitterviadukt Herisau-St. Gallen, Saaneviadukt Gümmenen) were built already with roller bearings to avoid longitudinal restraint of the steel girders. However, the masonry vaults next to the main span moved towards the river (ca. 270 mm on one pier in the Sitterviadukt) in the years after construction, due to partly irreversible temperature-induced elongations of the adjoining masonry viaducts, which evidently are not restrained by arch thrust at the main span. These bridges were therefore retrofitted around 1920 with so-called lever-arm devices (“Hebelvorrichtungen) providing a roughly constant horizontal compressive force to the masonry vaults (transferred by the steel girder). When replacing the main span of such a bridge today (such as in the Saaneviadukt Gümmenen), this aspect needs to be considered.

Photos: Rheinbrücke Eglisau, 1895/97, l=90 m (top) and Rheinbrücke Koblenz (bottom), from “Schweizer Eisenbahnbrücken”, © Georg Aerni

Support and articulation – Introduction

Hence, since the early days of iron bridges, most bridge girders were supported on bearings to allow unrestrained thermal expansion and contraction of the girders in order to:

- avoid damage to abutments due to imposed movements
- avoid restraint in bridge girder due to restrained deformations

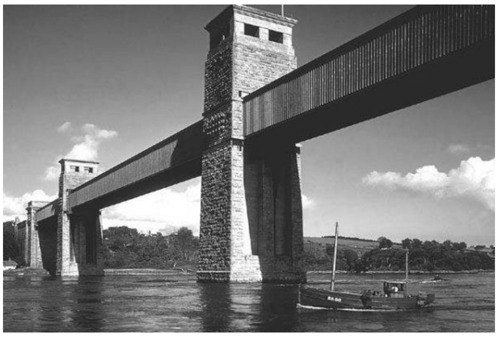
For example, the Britannia bridge (Robert Stephenson 1846/50, replaced 1972 after fire), used cast iron roller bearings on all but the central towers to allow sliding of the box girder. In the following decades,

→ providing statically determinate horizontal supports to bridge girders became common engineering practice

This paradigm was fostered by the advent of prestressing technology, since

- prestressing results in a contraction of the girder, causing tension if restrained
- shrinkage and creep of concrete are causing further contraction

→ pioneers of prestressing were very concerned that the beneficial effect of prestressing was lost (see notes)



In prestressed concrete bridges, in addition to temperature and shrinkage, the bridge girder contracts due to initial prestressing and subsequent creep caused by the compressive stresses in the concrete. If the contraction of the girder was completely restrained by the substructure, the anchor forces due to posttensioning would indeed act on the substructure, rather than on the girder as required. However, as outlined in the chapter on integral bridges, even very stiff bridge ends are much more flexible than the bridge girder, and therefore absorb only a small part of the prestressing force.

In the early days of prestressing, the concept of partial prestressing was unknown; structures were either non-prestressed or fully prestressed for all actions. Furthermore, other than today, the amount of prestressing forces resisted by the substructure could not be reliably estimated. Therefore, the pioneers of prestressing claimed that any restraint of the girder's contraction should be avoided. For example, in 1964 the eminent German Engineer Fritz Leonhardt insisted in the first of his *Ten Commandments for the prestressed concrete engineer*: “Prestressing means compressing the concrete. Compression can take place only where contraction is possible. Make sure that your structure can shorten in the direction of prestressing”. The French pioneer in prestressing, Eugène Freyssinet, published similarly dogmatic recommendations.

In addition, in the early days of reinforced concrete, knowledge on long-term effects in concrete (shrinkage, creep), essential to deal with restrained deformations, was limited. This was yet another reason for not impeding expansion or contraction of the bridge girder.

Photos: Britannia bridge © Godden Collection, Earthquake Engineering Research Center, University of California, Berkeley / Photos: Treskowbrücke, Berlin (1935) © N. Meng, K. Islami: Aussergewöhnliche Bauwerkslagerungen und Entwicklungen von intelligenten Brückenkomponenten, szs steelacademy, 2006

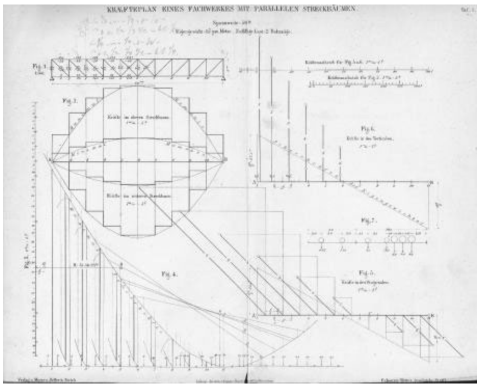
Support and articulation – Introduction

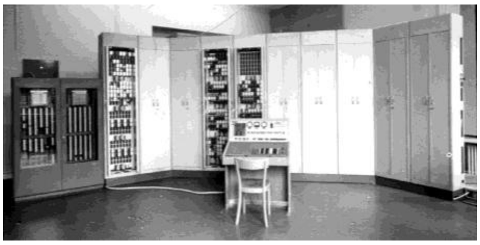
Another reason for providing bridge bearings was that

- the restraint forces in bridge girders, whose expansion or contraction is impeded by the substructure (abutments, piers), are difficult to quantify,
- particularly since they depend on soil-structure interaction

→ such analyses are perfectly feasible today but, they were beyond reach in the 19th century using hand calculations (e.g. modelling the soil stiffness by elastic springs means adding a degree of statical indeterminacy per spring).

- Suitable computational tools became available in the 1950s, particularly through the Finite Element Method (civil engineers significantly contributed to the development of this method, together with aeronautical engineers, and structural analysis was a first field of application of the FEM) but …





Until the 1980s, structural analysis software was installed on computers in electronic data processing centres, whose use was expensive or even restricted to researchers. The photo shows the “ERMETH” (Elektronische Rechenmaschine der ETH), developed by Prof. Eduard Stiefel at ETH 1948-56, 100 times faster than the predecessor Zuse Z4. The ERMETH was used until 1963, when it was decommissioned and replaced by a 400 times faster CDC 1604A computer (which, like ERMETH, was the only computer at ETH … roughly 100 times slower though 1000 times more expensive than a modern smartphone).

Illustration: Forces in a truss with parallel chords, from Culmann-Ritter, Die Graphische Statik
Photo: ERMETH, 1956-1963, © ETHistory

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→ user-friendly software programs running on powerful yet affordable computers, taken for granted as a standard tool of structural engineers today, only became reality in the 1990s.

FRIENDLINESS. Informative HP manuals, helpful error messages, and automatic syntax checking make BASIC language programming easy.

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When performance must be measured by results.

The first "personal computers" were usually shared by several engineers in an office due to the high cost (in spite of the extremely limited power compared to today's computers). As an example, a HP85 system (computer, printer and floppy disk drive), state-of-art in the 1980s, costing about CHF 18'000.- at the time (= ca.35 kCHF today) [Narayanan and Schneider, 1982], offered the following performance:

- CPU 8 bit running at 0.625 MHz
- 32 kB ROM (including BASIC programming language interpreter)
- 16 kB RAM (extendable to 640 kB, at CHF 2'500.- per 128 kB)
- CRT display 16 rows with 32 characters each / 256x192 px graphics

Photo: Advertisement for HP85 (1980) © hpmuseum.net

Support and articulation – Introduction

On the other hand:

- bridge girders provided with a horizontally statically determinate bearing layout can be analysed independently of the substructure
- supports facilitate the efficient erection of girder bridges

→ bridges provided with expansion joints and bearings, such that the girder can expand and contract freely, became very popular (particularly after World War II, when many developed countries were extending their motorway networks)

→ still today, many textbooks and guidelines worldwide presume implicitly that bridge girders are always articulated, i.e. provided with statically determinate horizontal supports

However, this paradigm is outdated, particularly for road bridges where de-icing salts are used – see following slides. Rather:

- the optimum support and articulation concept must be carefully chosen in the conceptual design phase for each bridge
- in many cases, avoiding expansion joints and bearings is preferable

Photo top Viaducto de Bunol © Pacadar SL

Photo bottom Brücke Linden (longest of the three precast concrete viaducts Linden, Mettlen and Boli) near Goldau, 1975 © Meichtry und Widmer.

Support and articulation – Introduction

The long-term experience with jointed bridges is extremely negative

- particularly in road bridges exposed to de-icing salts
- main problem = expansion joints in road bridges
- leaking expansion joints are a principal cause of bridge deterioration

→ may cause severe damage to the bridge structure, e.g.

→ trigger corrosion of bearings and anchorages of prestressing cables near the joints

Leaking expansion joints are a principal cause of bridge deterioration, particularly in road bridges, where runoff water loaded with de-icing salts penetrating leaking expansion joints may cause severe damage to the bridge structure, e.g. by triggering corrosion of bearings and anchorages of prestressing cables near the joints.

In road bridges with heavy traffic, even so-called “watertight” expansion joints are prone to leakage after a relatively short period of time, despite the use of higher quality sealing components (rubber profiles): Mechanical damage to these devices (indentation of gravel by truck wheels, snowploughs, ...) can hardly be avoided.

Photos: Überführung N1-525 Härdli and Fabrikkanäle N3/68 (roller bearing) before rehabilitation © dsp Inenieure+Planer

Support and articulation – Introduction

Furthermore, expansion joints are problematic regarding

- user comfort
- noise emissions
- robustness (e.g. earthquake resistance)

particularly if bearings and expansion joints are provided over intermediate supports.

This is different in railway bridges (see notes below and bearing layout principles).

In modern railway systems, continuously welded rails are standard and should be used on bridges wherever possible, since rail track expansion devices are expensive and require maintenance, increase the risk of derailment, affect user comfort and cause noise. Typically, compressive stresses in continuously welded rails are limited (to about 90 MPa) to avoid track instabilities; this is usually achieved if the bridge expansion joints are separated by no more than about 100 m.

Therefore, long railway viaducts are often subdivided into sections of roughly 90 m length, separated by intermediate bridge joints in order to avoid rail expansion devices, even if the bridge itself could be built without expansion joints over a much longer length. This is preferable since bridge expansion joints over intermediate piers are much less critical in railway bridges (no de-icing salts, bridge joints not directly loaded). Note that relative rotations between bridge end and abutment or among the girder ends of long viaducts may require transition slabs even if no rail expansion devices are needed, particularly in ballastless tracks.

To determine the stresses in continuously welded rails , the track-bridge interaction has to be taken into account. This requires relatively complex analyses, which are often carried out by the railway companies in order to account for their specific conditions and needs appropriately.

Photo: Gardiner expressway, Toronto © kfm

Support and articulation – Introduction

Damage caused by leaking expansion joints can be avoided if they

- are adequately designed and detailed
- ensure a controlled evacuation of runoff water even if the joints are leaking (see photos and section on abutments)

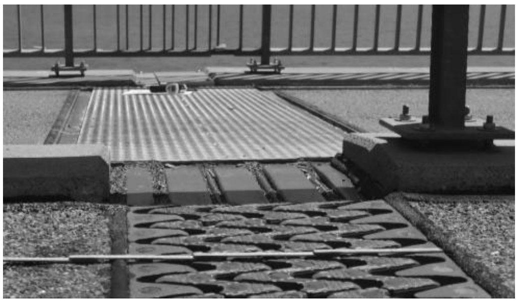
However, adequately detailed expansion joints (and the maintenance chamber required) are expensive but still

- require maintenance
- have a relatively short service life
- cause noise and harm user comfort

For these reasons, there is a strong tendency today to

→ avoid expansion joints in new road bridges

→ eliminate expansion joints at the time of bridge rehabilitation



Photos: Steinbachviadukt, details of expansion joint (roadway / walkway / parapet)

© dsp Ingenieure+Planer

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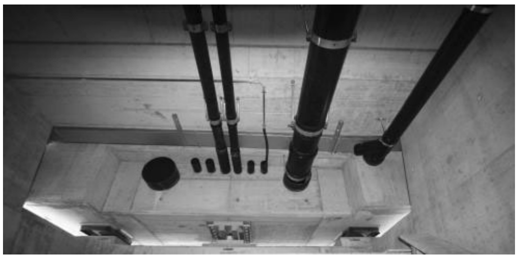


Photos: Steinbachviadukt (drainage of joint in maintenance chamber and under cantilevers)
© dsp Ingenieure+Planer

Support and articulation – Introduction

In modern bridge design, rather than blindly following the obsolete paradigm of horizontally isostatic support:

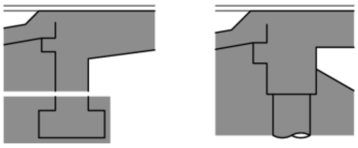
→ the optimum support and articulation concept must be carefully chosen in the conceptual design phase for each bridge

→ expansion joints and bearings should be avoided

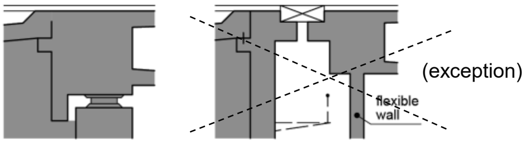
Many solutions are possible, that can be categorised based on

- the type of bridge end (see figure)
  … integral (neither expansion joint nor bearing)
  … semi-integral (bearing only, joint only in exceptional cases)
  … jointed (with expansion joint)
- the continuity of the girder
  … continuous (usual)
  … jointed (avoid, except in long railway viaducts)
- the connections of girder and piers
  … monolithic (preferred)
  … articulated with concrete hinges (quasi-monolithic)
  … articulated with bearings

Integral bridge ends (neither expansion joint nor bearing)



Semi-integral bridge ends (bearing only)



Jointed bridge ends (with expansion joint and bearing)

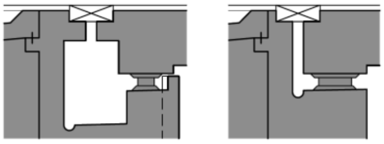


Figure: Astra Richtlinie 12004 Konstruktive Einzelheiten von Brücken, Fig. 1.1 (translated to English)

Support and articulation – Introduction

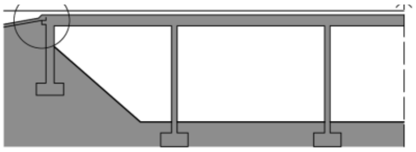
The support and articulation concept of a bridge can then be classified by

- the type of bridge ends (integral or articulated) and
- the continuity of the girder (with or without joints)
- the connections of girder to substructure (monolithic or articulated)

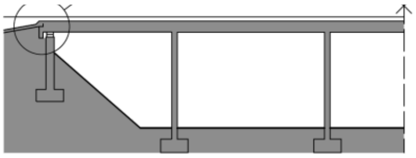
In this lecture, the following definitions are used:

<table>
<tr><th rowspan="2">detailing of girder and piers
detailing of bridge ends</th><th colspan="2">jointless girder</th><th rowspan="2">girder with joint(s)
</th></tr>
<tr><th>girder-pier connection monolithic</th><th>girder-pier connection articulated</th></tr>
<tr><td>both bridge ends integral</td><td>integral bridge</td><td></td><td rowspan="3">jointed bridge
(horizontally articulated to minimise restraint)</td></tr>
<tr><td>no bridge end with joint (but not both integral)</td><td colspan="2">semi-integral bridge</td></tr>
<tr><td>at least one bridge end articulated, with joint</td><td colspan="2">bridge hor. stabilised by piers</td></tr>
</table>

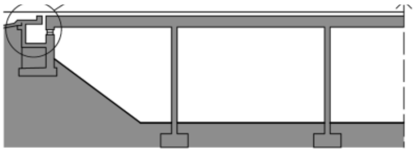
Integral bridge



Semi-integral bridge



Jointed bridge / bridge with expansion joints



Note that the terminology used for integral and semi-integral bridges varies considerably. For example, in a bridge horizontally stabilised by the piers, but with expansion joints at both bridge ends, is called “semi-integral” or even “integral” in some textbooks if the piers are monolithically connected to the girder.

Figures: Astra Richtlinie 12004 Konstruktive Einzelheiten von Brücken, Fig. 1.1 (translated to English and adapted)

Support and articulation

Girder deformations and movements

Support and articulation – Girder deformations

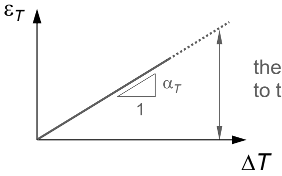
Expansion and contraction of bridge girders is caused by

- applied loads, particularly longitudinal prestressing
- temperature variation in all materials
- moisture variation in timber and concrete (“drying shrinkage”)
- shrinkage of concrete (autogenous and chemical) and FRP
- creep of concrete, timber and FRP

It should be observed that:

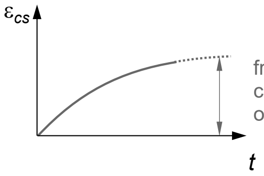
- expansion and contraction due to temperature variation, humidity changes and shrinkage are considered to be independent of applied stresses
- contraction due to prestressing (and hence creep) is approximately proportional to the applied stresses
- shrinkage and creep are time-dependent effects subject to high uncertainty (large scatter of values)
- in concrete, contraction due to moisture reduction is conventionally included in the shrinkage deformations, together with autogenous and chemical shrinkage

Temperature variation $\Delta_T \rightarrow \varepsilon_T = \alpha_T \cdot \Delta_T$



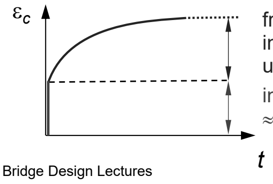
thermal strain ≈ proportional to temperature change

Shrinkage → ε_{cs}



free shrinkage strain = contraction independent of applied stress

Elastic deformation $\varepsilon_{c,el}$ + creep $\varepsilon_{cc} = \varphi \cdot \varepsilon_{c,el}$ ($\varphi \approx 1.8$)



free creep strain $\varepsilon_{cc} = \varphi \cdot \varepsilon_{c,el}$ increase of deformation under constant stress

initial (elastic) deformation $\varepsilon_{c,el}$ ≈ proportional to applied stress

Support and articulation – Girder deformations

Temperature variation

- uniform temperature variations of bridge girders
  … depend on the location of the bridge (climate)
  … are greater than ambient temperature variations
- in an unrestrained bridge girder, a uniform temperature difference ΔT causes a thermal strain proportional to ΔT and to the coefficient of thermal expansion α_T :

$$\varepsilon_T = \alpha_T \cdot \Delta T$$

- for steel and concrete $\alpha_T = 10 \cdot 10^{-6}$/K may be adopted (despite variations in reality, see notes)
- for timber, thermal effects are subordinate (moisture dominates) → many codes do not provide values for α_T
- for the choice of the support and articulation concept, differential temperature effects (temperature differences between top and bottom of girders) can be neglected
- the table illustrates uniform temperature differences and resulting thermal strains to be used in Swiss bridges (ASTRA) when determining the movement capacity of bearings and expansion joints (factor γ_F see next slide)

Thermal effects for design of bearings and expansion joints in Swiss road bridges (*)	Superstructure type		
	steel	composite	concrete
temperature variation ΔT_{1k} (SIA 261)	± 30°C	± 25°C	± 20°C
50% increase for design of bearings and expansion joints (SIA 261) (***)	± 15°C	± 12.5°C	± 10°C
ΔT_k to consider $\alpha_T \Delta T_k$ to consider	± 45°C $\pm 450 \cdot 10^{-6}$	± 37.5°C $\pm 375 \cdot 10^{-6}$	± 30°C $\pm 300 \cdot 10^{-6}$
$\gamma_F \cdot \alpha_T \Delta T_k$ (*)	$\pm 675 \cdot 10^{-6}$	$\pm 563 \cdot 10^{-6}$	$\pm 450 \cdot 10^{-6}$

(*) reference temperature +10°C unless otherwise specified
(**) according to ASTRA guideline 12004: γ_F=1.5 if temperature is the leading variable action, accounts for uncertainties in α_T, position of fixed point, temperature at installation etc.
(***) accounts for difference between ambient temperature variation and bridge temperature variation, see also notes

In reality, the coefficient of thermal expansion α_T varies, with values in the following range:

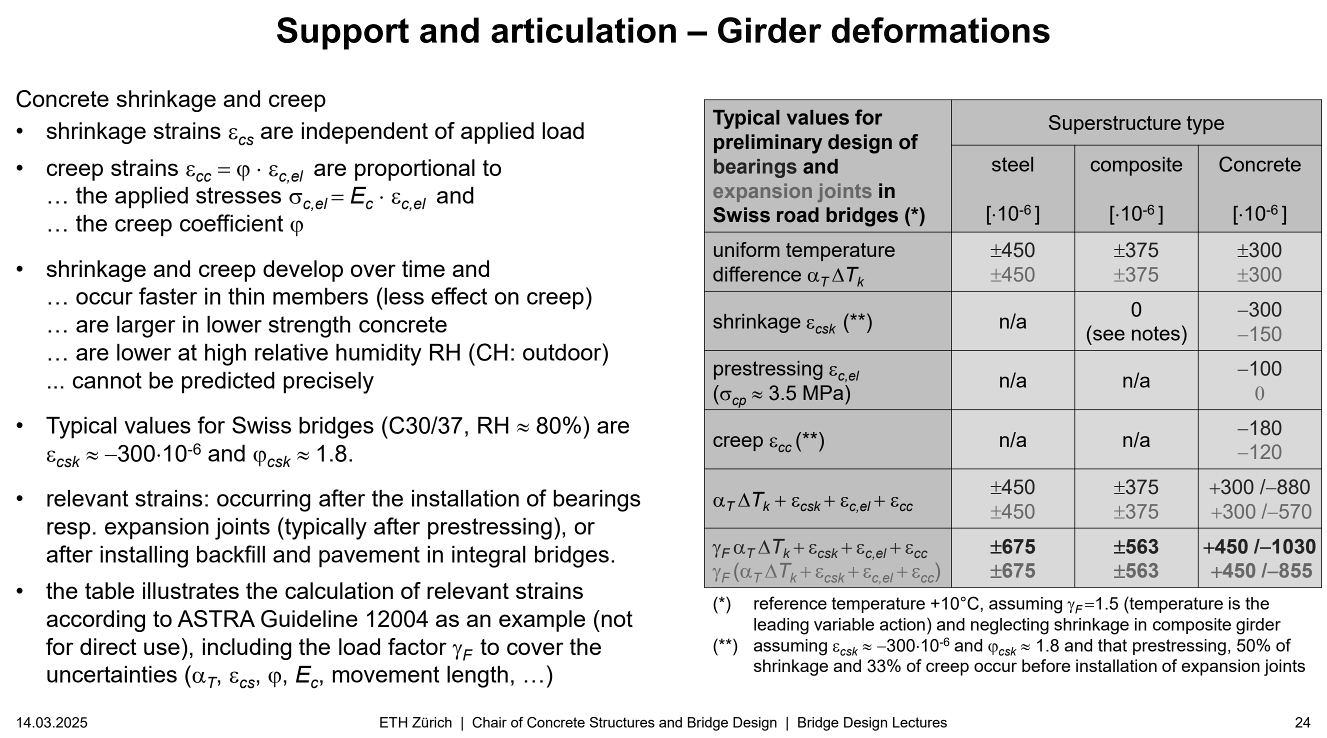
• steel:	$\alpha_T = 9 \ldots 15 \cdot 10^{-6}$/K	(higher for stainless steel)
• concrete:	$\alpha_T = 6 \ldots 15 \cdot 10^{-6}$/K	(depends on aggregates)
• timber:	$\alpha_T \approx 3 \ldots 5 \cdot 10^{-6}$/K	(parallel to grain)
	$\alpha_T \approx 30 \cdot 10^{-6}$/K	(across grain)
• FRP:	$\alpha_T \approx 5 \ldots 25 \cdot 10^{-6}$/K	(depends on product)

For structural steel $\alpha_T = 12 \cdot 10^{-6}$/K would be more appropriate than $10 \cdot 10^{-6}$/K; the same value for concrete and steel is adopted primarily to avoid having to account for restraint caused by different values (that in reality occurs, however).

In thick concrete members, hydration heat effects (contraction due to cooling of concrete) should also be considered.

In integral bridges, neither the increase of 50% (SIA 260) nor the additional γ_F=1.5 have to be considered for checking bridge end movements, see integral and semi-integral bridges.

The difference beween ambient temperature and bridge temperature is accounted for by increasing the temperature variation by a factor of 1.5 in SIA 260, see table footnote. EN 1991-2 provides a more refined method of obtaining bridge temperature variations based on ambient temperature, which may be more adequate particularly for cold temperatures (e.g. concrete bridges do not get colder than the ambient temperature in most locations).



Support and articulation – Girder deformations

Concrete shrinkage and creep

- shrinkage strains ε_{cs} are independent of applied load
- creep strains $\varepsilon_{cc} = \varphi \cdot \varepsilon_{c,el}$ are proportional to
  … the applied stresses $\sigma_{c,el} = E_c \cdot \varepsilon_{c,el}$ and
  … the creep coefficient φ
- shrinkage and creep develop over time and
  … occur faster in thin members (less effect on creep)
  … are larger in lower strength concrete
  … are lower at high relative humidity RH (CH: outdoor)
  ... cannot be predicted precisely
- Typical values for Swiss bridges (C30/37, RH ≈ 80%) are $\varepsilon_{csk} \approx -300 \cdot 10^{-6}$ and $\varphi_{csk} \approx 1.8$.
- relevant strains: occurring after the installation of bearings resp. expansion joints (typically after prestressing), or after installing backfill and pavement in integral bridges.
- the table illustrates the calculation of relevant strains according to ASTRA Guideline 12004 as an example (not for direct use), including the load factor γ_F to cover the uncertainties (α_T, ε_{cs}, φ, E_c, movement length, …)

Typical values for preliminary design of bearings and expansion joints in Swiss road bridges (*)	Superstructure type		
	steel $[\cdot 10^{-6}]$	composite $[\cdot 10^{-6}]$	Concrete $[\cdot 10^{-6}]$
uniform temperature difference $\alpha_T \Delta T_k$	±450 ±450	±375 ±375	±300 ±300
shrinkage ε_{csk} (**)	n/a	0 (see notes)	–300 –150
prestressing $\varepsilon_{c,el}$ ($\sigma_{cp} \approx 3.5$ MPa)	n/a	n/a	–100 0
creep ε_{cc} (**)	n/a	n/a	–180 –120
$\alpha_T \Delta T_k + \varepsilon_{csk} + \varepsilon_{c,el} + \varepsilon_{cc}$	±450 ±450	±375 ±375	+300 /–880 +300 /–570
$\gamma_F \alpha_T \Delta T_k + \varepsilon_{csk} + \varepsilon_{c,el} + \varepsilon_{cc}$ $\gamma_F (\alpha_T \Delta T_k + \varepsilon_{csk} + \varepsilon_{c,el} + \varepsilon_{cc})$	**±675** **±675**	**±563** **±563**	**+450 /–1030** **+450 /–855**

(*) reference temperature +10°C, assuming γ_F=1.5 (temperature is the leading variable action) and neglecting shrinkage in composite girder

(**) assuming $\varepsilon_{csk} \approx -300 \cdot 10^{-6}$ and $\varphi_{csk} \approx 1.8$ and that prestressing, 50% of shrinkage and 33% of creep occur before installation of expansion joints

Time dependent effects are dealt with in detail in the lecture Advanced Structural Concrete, see there for more details on determining shrinkage strains and creep coefficients. Here, only the unrestrained values (free thermal, shrinkage, and creep strains) are of interest. These can simply be determined based on the values provided by design codes (since the prestressing force P decreases over time due to relaxation and creep, a force of $(P_{t=0} + P_{t=\infty})/2$ is usually adopted to calculate creep strains). For integral bridges, as well as the design of piers with hinged or monolithic connection to the girder, further considerations apply, see respective slides (substructure chapter).

The table illustrates the calculation of relevant strains for the calculation of the required movement capacity of bearings and expansion joints according to ASTRA Guideline 12004, as an example (not for direct use in design). For simplification, it is assumed that temperature is governing as leading action, i.e. only the combination $\gamma_F \alpha_T \Delta T_k + \varepsilon_{csk} + \varepsilon_{c,el} + \varepsilon_{cc}$ is considered for bearings, and the combination $\gamma_F (\alpha_T \Delta T_k + \varepsilon_{csk} + \varepsilon_{c,el} + \varepsilon_{cc})$ for expansion joints, both with γ_F=1.5. For the design of bearings, an alternative combination with material properties as leading action should also be considered, i.e. $\alpha_T \Delta T_k + \gamma_F (\varepsilon_{csk} + \varepsilon_{c,el} + \varepsilon_{cc})$, with γ_F=1.35 (which would result in values of $+300 \cdot 10^{-6}$ /$-880 \cdot 10^{-6}$ rather than $+450 \cdot 10^{-6}$ /$-1030 \cdot 10^{-6}$, i.e., is not governing in this specific case.

Compared to other (international) standards, the resulting movements are rather high, which is due to the fact that ASTRA decided to provide a relatively large safety margin (factor γ_F) to avoid failures of bearings or expansion joints due to insufficient movement capacity. For bearings, providing more movement capacity is usually inexpensive (longer steel sliding plate only). For expansion joints, a higher movement capacity may cause high costs and/or require using a less robust type of joint. Therefore, a reduction to γ_F =1.25 is allowed for expansion joints if detailed analyses are carried out.

In composite girders, shrinkage of the deck slab is restrained by the steel girders and often causes only negligible longitudinal strains. In cases with thick slabs on light girders, shrinkage may however have to be considered.

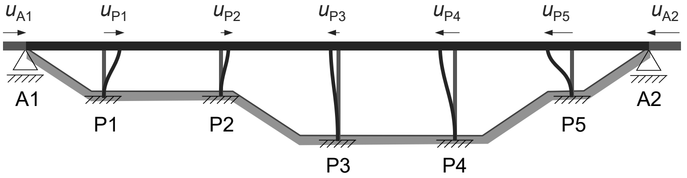
Support and articulation – Girder movements

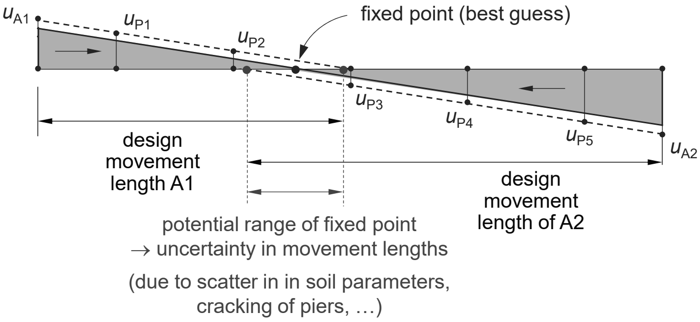
Movements of the bridge girder

- temperature variations, shrinkage, prestressing, creep and moisture variation cause strains of the girder
- order of magnitude of characteristic total strains:
  … composite $\varepsilon_k \approx$ $750 \cdot 10^{-6}$ ($\pm$ 375)
  … steel $\varepsilon_k \approx$ $900 \cdot 10^{-6}$ ($\pm$ 450)
  … concrete $\varepsilon_k \approx$ $1200 \cdot 10^{-6}$ (+300/-900) for bearings
  $\varepsilon_k \approx$ $900 \cdot 10^{-6}$ (+300/-600) for exp. joints
- these strains cause movements of the girder, that increase in proportion with the distance ("movement length") from the point of zero movement ("fixed point")
- unless the girder is fixed longitudinally at an abutment, the position of the fixed point is not exactly known
- the relevant movement lengths vary in staged construction, but only movements occurring after the installation of bearings and joints (or backfill and pavement in integral abutments) need to be considered

→ consider construction process (allocating adequate reserve capacities, particularly in case of bearings and expansion joints, see substructure chapter for details)

Movements due to girder contraction
(schematic, bridge longitudinally stabilised by piers)





potential range of fixed point
→ uncertainty in movement lengths

(due to scatter in in soil parameters, cracking of piers, …)

Support and articulation – Girder movements

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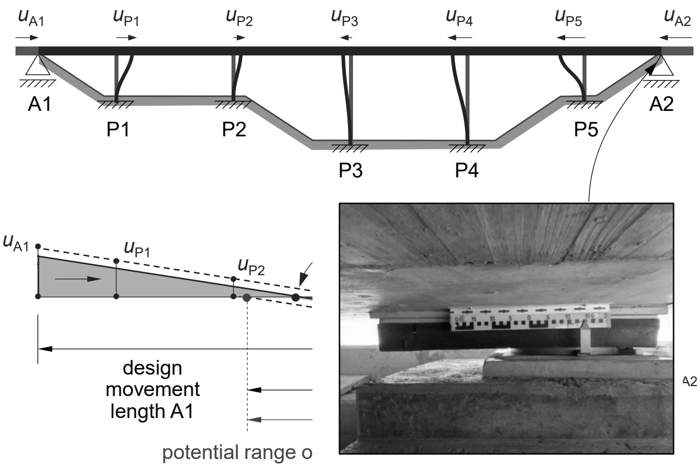


potential range o
→ uncertainty in movement lengths

(due to scatter in in soil parameters,
cracking of piers, …)

Support and articulation – Girder movements

Movements of bridge girder

- relevant movements of the girder are also caused by
  … horizontal loads (braking, acceleration, …)
  … vertical loads in arches, frames, …
- these loads cause a rigid body motion of the girder unless the girder is fixed longitudinally at an abutment

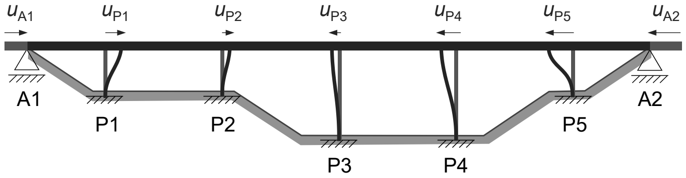
→ total girder movements = deformations (expansion / contraction) + rigid body movements of girder

→ the total movements are relevant for the design of the piers (e.g. monolithic connection of short piers near abutments possible?) and integral bridge ends

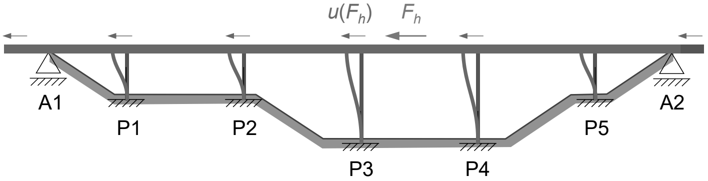
→ in jointed bridges, movable bearings and expansion joints need to be provided with sufficient movement capacity to accomodate the total movements with adequate reserves (e.g. using a load factor γ_F as required by ASTRA)

→ the total characteristic movements of the bridge ends are the basic criterion for the suitability of integral and semi-integral bridge ends (see integral bridges)

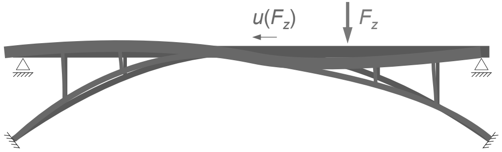
Movements due to girder contraction
(schematic, bridge longitudinally stabilised by piers)



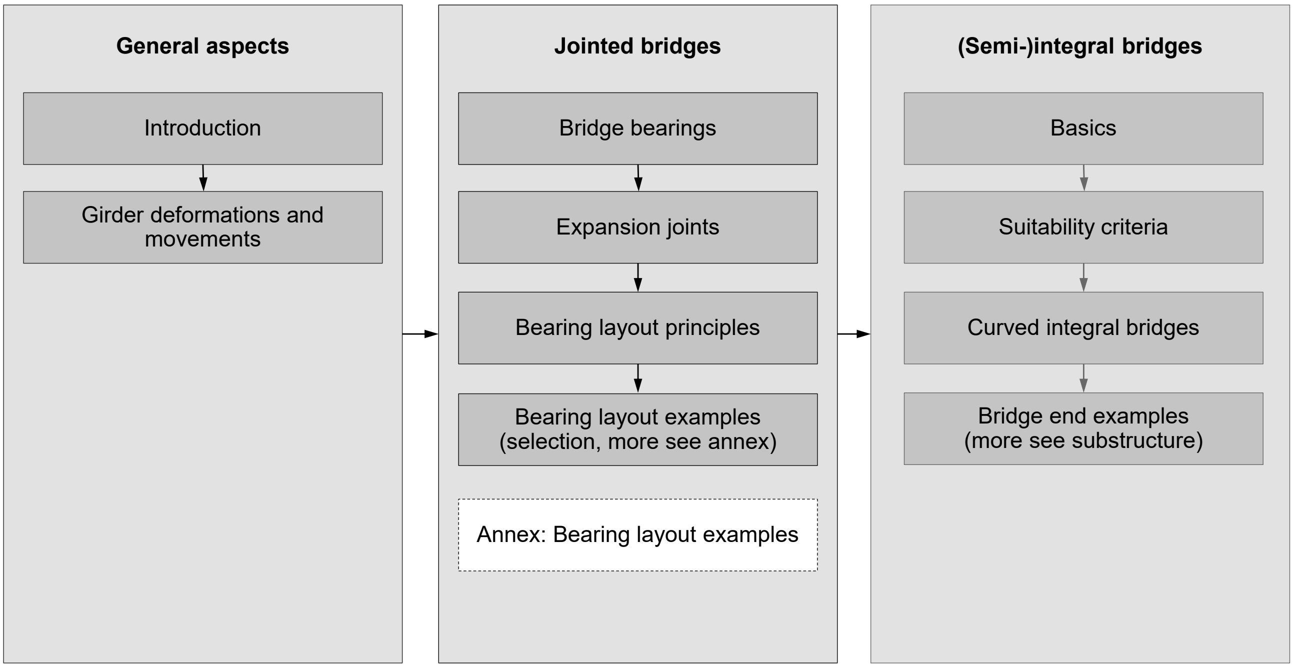
Movements due to horizontal load (schematic)



Horizontal movements due to vertical load (schematic)



Movements of the girder to be considered for the expansion joints further include horizontal movements at the level of the expansion joint caused by girder end rotations (see jointed bridges – bearing layout); they can be estimated by assuming a girder end rotation of ca. 4 mrad (corresponding to a midspan deflection of ca. L/1000 under traffic loads), which is multiplied by the vertical distance of the expansion joint from the support = axis of rotation (e.g. for a girder depth of 2 m, roughly 8 mm additional movement is obtained).



General aspects

- Introduction
- Girder deformations and movements

Jointed bridges

- Bridge bearings
- Expansion joints
- Bearing layout principles
- Bearing layout examples (selection, more see annex)
- Annex: Bearing layout examples

(Semi-)integral bridges

- Basics
- Suitability criteria
- Curved integral bridges
- Bridge end examples (more see substructure)

Support and articulation

Jointed bridges – Bearings and expansion joints

Support and articulation – Jointed bridges

Expansion joints and bearings cannot be avoided in all cases. In particular, a horizontal articulation (“dilatation”) is required

- in long bridges (limits see *integral bridges*)
- at low abutments or short piers on stiff soil
- if ductility of the girder is a concern (existing bridges, steel bridges with slender elements, timber bridges)

In such cases, bearings and expansion joints are used to provide articulation; in particular to

- minimise restraint to expansion and contraction of the bridge girder,
- accommodate the movements of the bridge girder with adequate reserve capacity (bearings and expansion joints)
- enable rotations of the girder with minimum restraint
  (if rotation is intentionally impeded, such as torsional rotation restraint, two bearings are usually provided → force couple)

At abutments, movements are usually guided in one direction, since multiaxial movements require more complicated expansion joints (except at small movements where a single profile joint is sufficient).

Top photo: Viadukt Glattzentrum; narrow-gauge railway, twin pier (to avoid railway track expansion devices) with pot bearings on top. © dsp Ingenieure+Planer / mageba

Bottom photo: Pont du Tiguelet; road bridge, piers with pot bearings. Both bearings on top of each pier are movable longitudinally (direction of bridge axis). One bearing per pier is also movable in the transverse direction, the other one is fixed in that direction, providing transverse support to the girder. © dsp Ingenieure+Planer

Support and articulation – Jointed bridges

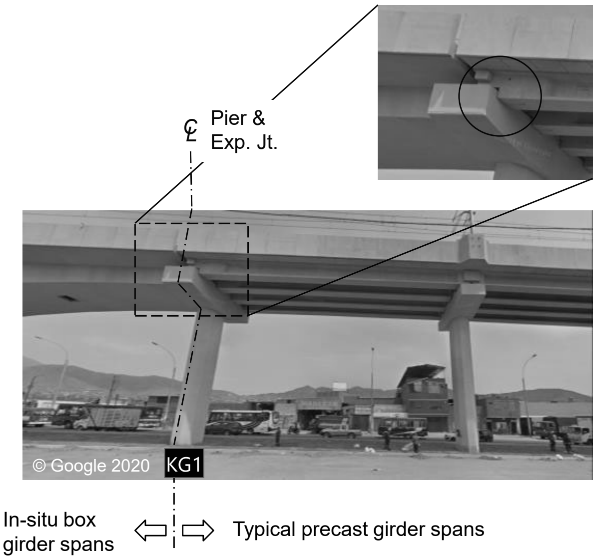
Bearings and expansion joints – if provided – are decisive for the structural safety, serviceability and durability of bridges

- → classic textbook treatment as “bridge accessories” or “bridge equipment” is misleading (see photo and notes on next slide)
- → bearings and expansion joints merit the same degree of attention of bridge engineers as the bridge structure itself

despite the fact that bridge bearings and expansion joints are standardised today (see notes), which allocates much of the responsibility for their proper functioning with the supplier.

The treatment of bearings and expansion joints as “accessories”, dealt with as an afterthought of designers at a late design stage, may cause severe problems.

This is even more critical if bearings and expansion joints are located at the demarcation of responsibilities of different design teams or even firms, e.g. between two parts of a long bridge, or – more often – between substructure and superstructure.



European standards for road bridge expansion joints and bridge bearings:

ETAG no. 032 Guideline for European Technical Approval of Expansion Joints for Road Bridges, European Organisation for Technical Approval

Part 1: General
Part 2: Buried expansion joints
Part 3: Flexible plug expansion joints
Part 4: Nosing expansion joints
Part 5: Mat expansion joints
Part 6: Cantilever expansion joints
Part 7: Supported expansion joints
Part 8: Modular expansion joints

EN1337 Structural Bearings

Part 1: General design rules EN 1337-1:2000
Part 2: Sliding elements EN 1337-2:2004
Part 3: Elastomeric bearings EN 1337-3:2006
Part 4: Roller bearings EN 1337-4:2005
Part 5: Pot bearings EN 1337-5:2006
Part 6: Rocker bearings EN 1337-6:2005
Part 7: Spherical and cylindrical PTFE bearings EN 1337-7:2004
Part 8: Guide bearings and restraint bearings EN 1337-8:2007
Part 9: Protection EN 1337-9:1997
Part 10: Inspection and maintenance EN 1337-10:2001
Part 11: Transport, storage and installation EN 1337-11:1997

Support and articulation – Jointed bridges

The following must be kept in mind when designing bearings and expansion joints:

→ Meticulously review (project-specific) performance and testing requirements by owner / supervisory agency / code)

→ Confirm that the supplier has corresponding approvals early in the process (specific additional testing and certification takes much time)

→ Allocate sufficient space for bearings and expansion joints in early design stages, accounting for possible changes of the supplier (products may differ substantially in size)

→ Provide access and sufficient clearances for maintenance and exchange of bearings and, in particular, expansion joints: They will need to be exchanged several times during the lifespan of the bridge

→ Check structural safety of substructure and superstructure (diaphragms) for the loads during bearing replacement (flat jacks will support the bridge at other locations than the bearings)

→ Consider all construction stages and time-dependent effects, as well as the installation temperature, when setting the expansion joints and bearings during installation (there is no safety factor on geometry)

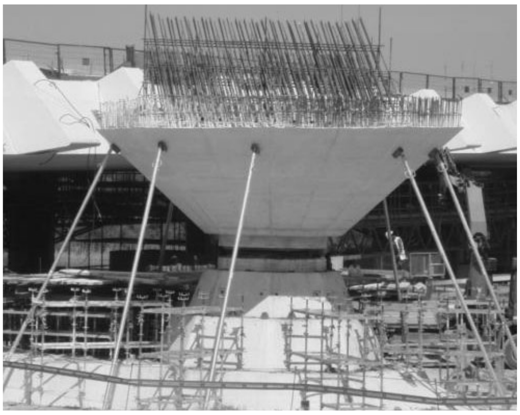


Photo: Puente del Tercer Milenio, Zaragoza: Bearing for characteristic vertical load of 82.5 MN and movements of about 100 mm (elastomer Ø2100 mm, steel plates Ø2300 mm): An “accessory” or “equipment”? © Arenas & Asociados

Support and articulation – Jointed bridges

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Video: Qualification testing against fatigue © mageba

Support and articulation

Jointed bridges – Bridge bearings

Support and articulation – Bridge bearings

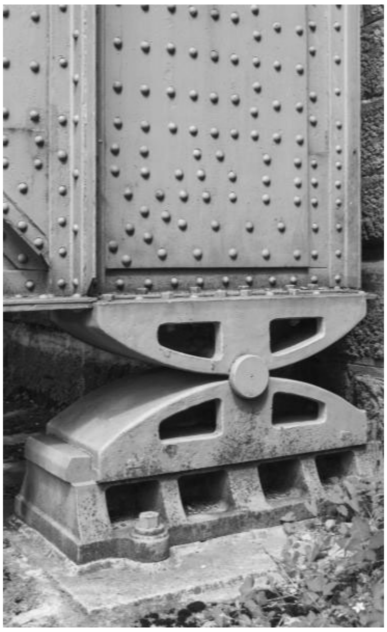
Many different types of bridge bearings exist. In older bridges, mainly steel bearings were used, such as:

- line or point rocker bearings
- roller bearings
- pin / leaf bearings
- …

Many of these bearing types accommodated rotation only around one axis

→ had to be positioned with care to avoid unwanted moment restraint of single bearings (usually in pairs of two along an intended axis of rotation)

→ on older drawings, bearing rotation axes were indicated (with a solid line) …
… but most modern bearings accommodate rotations around all axes without relevant restraint → rotation axes are no longer indicated usually (see e.g. EN1337-1)



Photos: Pin/leaf bearing (right) © Georg Aerni; Line rocker bearing (left top) © Emch+Berger; fixed roller bearing (left bottom) © dsp Ingenieure + Planer AG

Support and articulation – Bridge bearings

Today, the following types of bridge bearings (see following slides) are mainly used:

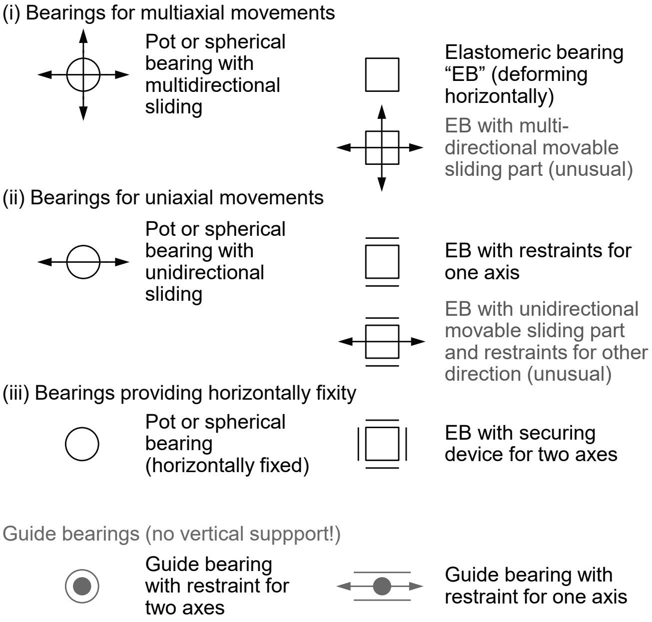
- Elastomeric bearings («Elastomerlager»)
- Pot bearings («Topflager»)
- Spherical bearings («Kalottenlager»)
- Guide bearings («Führungslager»)

All of these enable rotations around all axes with little restraint. All of these, except the guide bearings, provide vertical support and are available in configurations that

(i) accommodate multiaxial horizontal movements with little restraint (without providing horizontal fixity)
(ii) accommodate uniaxial horizontal movements with little restraint (while providing fixity in the other direction)
(iii) provide horizontal fixity

On bearing layouts drawings, the symbols shown on the right are commonly used today; see EN1337-1 for more details and other types of bearings.

For hinged connections, concrete hinges are a viable alternative to mechanical bearings, see also following slides.



(i) Bearings for multiaxial movements

Pot or spherical bearing with multidirectional sliding

Elastomeric bearing "EB" (deforming horizontally)

EB with multi-directional movable sliding part (unusual)

(ii) Bearings for uniaxial movements

Pot or spherical bearing with unidirectional sliding

EB with restraints for one axis

EB with unidirectional movable sliding part and restraints for other direction (unusual)

(iii) Bearings providing horizontally fixity

Pot or spherical bearing (horizontally fixed)

EB with securing device for two axes

Guide bearings (no vertical suppport!)

Guide bearing with restraint for two axes

Guide bearing with restraint for one axis

Notes:

For pot and spherical bearings, EN1337-1 indicates the directions of movement with arrows (since these types of bearing are horizontally fixed by default, requiring sliding plates to enable movements). For elastomeric bearings, the guides hindering movements are shown (as these bearings enable deformation in any direction by default, requiring guides to provide fixity).

For concrete hinges, there are no generally accepted conventions on symbols (indicate specific characteristics on drawing).

Support and articulation – Bridge bearings

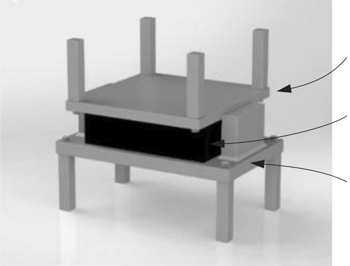
Elastomeric bearings (“Blocklager”, “Verformungslager”)

- accommodate moderate rotations with low restraint by deformation of the elastomer
- ensure a reasonably uniform bearing pressure
- accommodate horizontal movements with little restraint by shearing of the elastomer (unless guided)
- need only be anchored if a minimum contact pressure cannot be guaranteed

→ economic solution for small movements (variants with additional sliding plates for larger movements shown on previous slide are unusual → pot bearings)

The following should be observed:

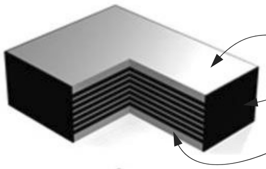
- non-anchored bearings can be replaced more easily; if anchored, make sure replacement is possible
- movement and rotation capacity depend on level of applied load (lower at higher vertical load)
- support reactions are eccentric (and slightly inclined) → pot bearings preferred on piers
- may be used for seismic isolation (for high seismicity: “lead rubber bearings” with higher damping)



top anchor plate (with sliding material on two side faces in uniaxial bearings)

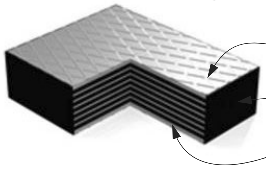
laminated bearing pad (with steel plates for fixation to top/bottom plates)

bottom anchor plate with guides (in uniaxial bearings only)



anchored bearing pad (as above)

- steel plate for fixation
- alternating layers of elastomer and steel plates (fully embedded)
- steel plate for fixation



bearing pad relying on friction

- checkerboard or rubber plate
- alternating layers of elastomer and steel plates (fully embedded)
- checkerboard or rubber plate

Bearing dimensions may *roughly* be estimated using the following data (see supplier specifications for details):

- elastomer pad pressure at maximum service loads (characteristic loads) ≈ 20 MPa
- shear modulus of elastomer $G \approx 1$ MPa, $\nu \approx 0.5$
  (hence $E = G \cdot 2(1+\nu) \approx 3$ MPa, but more flexible axially since rubber deforms horizontally)
- movement capacity ≈ 50% of total elastomer thickness (≈ 30% of height including steel plates) for long-term movements, ≈ 70% of total elastomer thickness when including dynamic actions (e.g. braking forces)

Note that for given dimensions in plan, the height of the bearings cannot be increased deliberately to accommodate large movements (instability, see supplier specifications for details).

Photos © mageba

Support and articulation – Bridge bearings

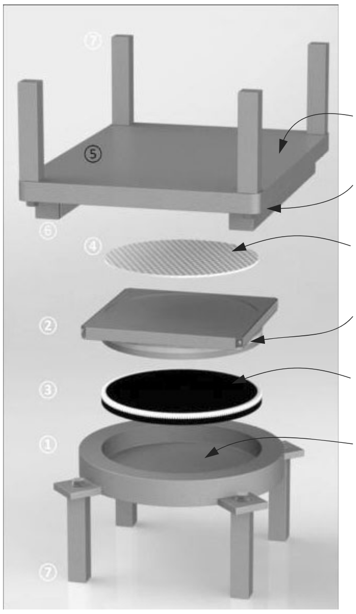
Pot bearings (“Topflager”)

- accommodate rotations by deformation of an elastomeric disc subjected to high pressure (behaving like a fluid) in a pot below the piston
- ensure uniform bearing pressure (elastomeric disc)
- may accommodate horizontal movements by sliding of a steel plate on a sliding pad on top of the piston
- are always anchored to the structure

→ adequate solution for moderate-large movements

The sliding material behaviour is of particular interest:

- PTFE is subject to wear (mainly due to length and speed of movements, expected lifespan ≈ 10-20 km)
- the friction coefficient of PTFE is higher at low temperatures and significantly higher at low pressure ($\mu \approx 3\%$ for 30 MPa , 8% for 5 MPa)
  → do not use larger sliding bearings than required
- high-tech sliding materials (e.g. ROBOSLIDE ® developed by mageba) with improved characteristics (friction, wear) are available



sliding plate with anchors
(sliding bearings only)

guide profiles
(unidirectional sliding bearings only)

sliding pad fixed on piston
(sliding bearings only)

piston (with sliding material on two side faces in uniaxial sliding bearings)

elastomeric disc (surrounded by sealing chain)

steel pot with anchors

In unidirectional sliding bearings, internal guides are also common (protruding from piston, indentation in sliding plate)

Bearing dimensions may *roughly* be estimated using the following data (see supplier specifications for details):

- elastomeric pressure at max. service loads ≈ 30 MPa
- pot wall thickness can be determined using Barlow’s formula (“Kesselformel”)

Photos © mageba

Support and articulation – Bridge bearings

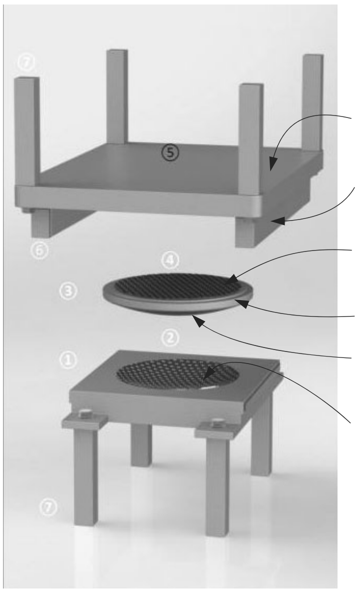
Spherical bearings (“Kalottenlager”)

- accommodate rotations by sliding of a spherical cap in a concave plate, with sliding surfaces on top and bottom side
- ensure reasonably uniform bearing pressure by high precision contact surfaces and stiff plates
- may accommodate horizontal movements by sliding of a steel plate on the sliding pad on top of the cap
- are always anchored to the structure
- are smaller than pot or elastomeric bearings, but more expensive

→ adequate solution if space is limited (e.g. on pier top)

The following should be observed:

- concrete strength of girder and substructure may be critical due to higher pressures (smaller dimensions)
- the rotation centre is between contact surfaces if two sliding planes are provided (as in figure; otherwise see notes)



sliding plate with anchors
(sliding bearings only)

guide profiles
(unidirectional sliding bearings only)

sliding pad fixed on top of spherical cap (sliding bearings only)

spherical cap (“Kalotte”)

sliding coating on bottom of spherical cap

concave bottom plate with anchors
(and sliding material on two side faces in uniaxial sliding bearings)

If the upper sliding plane is omitted, the rotation centre is far from the bearing (at the sphere centre); such bearings may be used to resist horizontal forces coupled with bending moments in girder (used e.g. for seismic applications in Italy)

Photos © mageba

Support and articulation – Bridge bearings

Concrete hinges (“Betongelenke”)

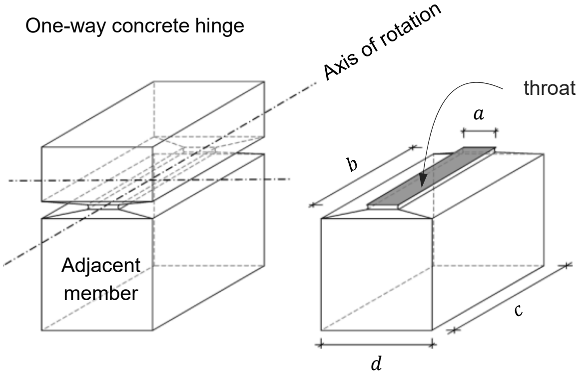
- combine the advantages of monolithic connections and hinged connections:
  … are virtually maintenance-free
  … accommodate rotations (up to ca. 15 mrad)
- provide little restraint to rotation by reducing the contact area to a narrow throat (“Gelenkhals”)
- resist very high axial loads due to multiaxial compressive stress state in the throat
- require less space than mechanical bearings

→ economic and durable solution for hinged connections with high vertical loads and limited space

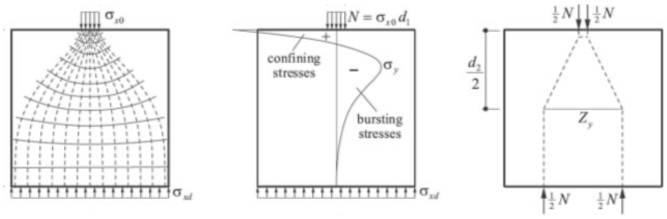
The following should be observed:

- provide adequate transverse reinforcement to resist bursting stresses («Spreizkräfte»)
- dimensioning (vertical load, rotation capacity) currently relies on empirical rules from the 1950’s
- mechanically based models and design rules are currently being developed

One-way concrete hinge



Bursting reinforcement



The multiaxial compressive stress state in the throat is due to a combination of geometrical confinement (as in partial area loading) and passive confinement by reinforcement next to throat (as in confined columns). The superposition of these effects is not straightforward, and currently being investigated at the Chair of Concrete Structures and Bridge Design.

If large horizontal movements have to be accommodated, struts with concrete hinges on top and bottom can be provided, such as in the spandrel piers of Tamina Bridge.

Long-term experience includes many bridges, such as e.g. the Hardturmviadukt in Zurich.

Support and articulation – Bridge bearings

Photo: Tamina Bridge near Bad Ragaz, LAP (2017). © TBA Kanton St. Gallen

Support and articulation – Bridge bearings

Special bearings

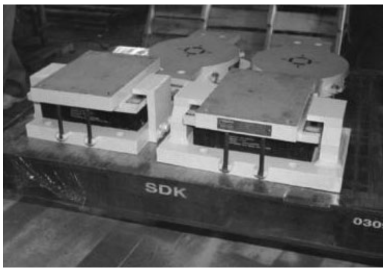
Many different types of bearings exist, that are useful for specific applications.

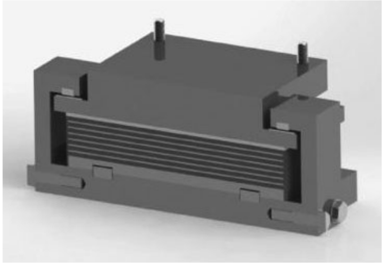
The following are illustrated on the right:

- Top: Guide bearings (photo: transverse horizontal restraint)

- Bottom: Uplift bearings







Photos credits

- top uniaxial guide bearing, Steinbachviadukt © W. Köhler, dsp Ingenieure+Planer

- Bottom elastomeric uplift bearings of Revere Beach Pedestrian Bridge © mageba (G. Moor, T. Spuler, N. Meng: Uplift bearings—selection and design considerations)

Support and articulation – Bridge bearings

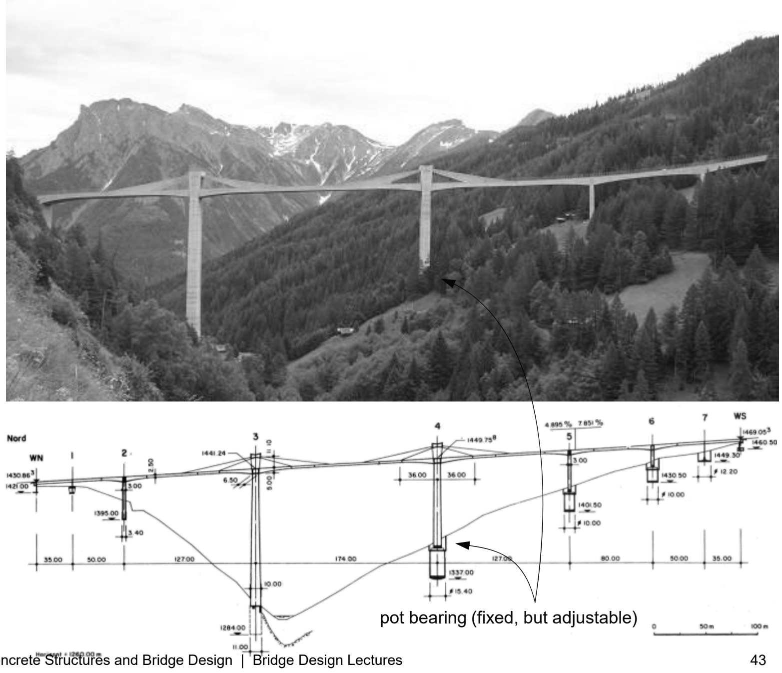
Special applications

Bearings may also be used to accommodate movements of the subsoil.

For example, the Ganter Bridge is provided with huge pot bearings at the pier base located on the left, unstable valley slope, that provide a hinged connection to the shaft foundation and would allow adjusting the (horizontal) position in case of excessive rock sliding.

During free cantilevering of the girder, the pier was fixed to the shaft foundation with concrete blocks and prestressing.

Since the bridge was designed such that fairly large movements can be accommodated without adjusting the bearings, only one adjustment was required to date (in 2006, according to information provided by mageba AG).



pot bearing (fixed, but adjustable)

- Ganter Bridge, 1908. Main span 174 m. Designer Ch. Menn with Schneller-Schmidhalter-Ritz Photo © Nicolas Janberg, structurae.de

Support and articulation

Jointed bridges – Expansion joints

Support and articulation – Expansion joints

Many different types of expansion joints exist, with significant differences depending on bridge use and movement capacity:

- in road bridges, expansion joints are the road surface, directly loaded by truck wheels and exposed to runoff water with chlorides

→ very high demand (see also notes) on
… strength, robustness (particularly against snow plough impact)
… watertightness
… user comfort and noise emissions

- in footbridges, loads are much less severe

→ simpler solutions possible (must avoid “bike traps”)

- in railway bridges, the bridge expansion joints are not loaded by traffic and no de-icing salts are used

→ simpler solutions possible for bridge expansion joints
→ but railway track expansion devices are highly complex (→ avoid)

On the following slides, usual expansion joints for road bridges (roadway joints) are illustrated. Rail track expansion devices are not dealt with as they are not designed by bridge engineers (but: avoiding them is a goal of railway bridge support and articulation concepts).

Note: Due to the heavy loads and exposure, the lifespan of expansion joints is much shorter than that of a bridge (approximately 20…30 vs 100 years). If expansion joints are improperly selected (e.g. regarding vertical offsets), the lifespan will be even shorter. Expansion joints in curves, or even crossings are also prone to premature deterioration (turning trucks generate high horizontal forces that expansion joints are not designed for).

Photos: Top Skew finger joint at Zürich Nordring © mageba; bottom Rail track expansion device on ballastless track, Oelztalbrücke © Creative commons

Support and articulation – Expansion joints

Flexible plug joint (“Fahrbahnübergang aus Polymerbitumen”)
(aka “Thorma Joint” in CH)

- are integrated in the pavement, without mechanical connection to the deck
- require no mechanical parts
- provide a smooth ride, with hardly any noise and good user comfort
- typical movement capacity: 30 mm (+20/-10 mm)

→ only suitable for very small movements

The following should be observed:

- for such small movements, integral abutments without expansion joint are usually possible
- With internal stabilising elements, movement capacity would be up to 100 mm, but many clients (e.g. ASTRA) do not allow such joints (unsatisfactory experience)
- proper installation is decisive for durability
- suitable for repair of pavement cracks behind integral bridge ends or as replacement of mechanical joints in existing bridges with small movements

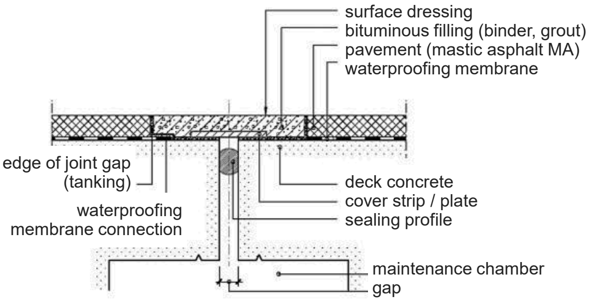


Figure © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Photos © rsag.ch

Support and articulation – Expansion joints

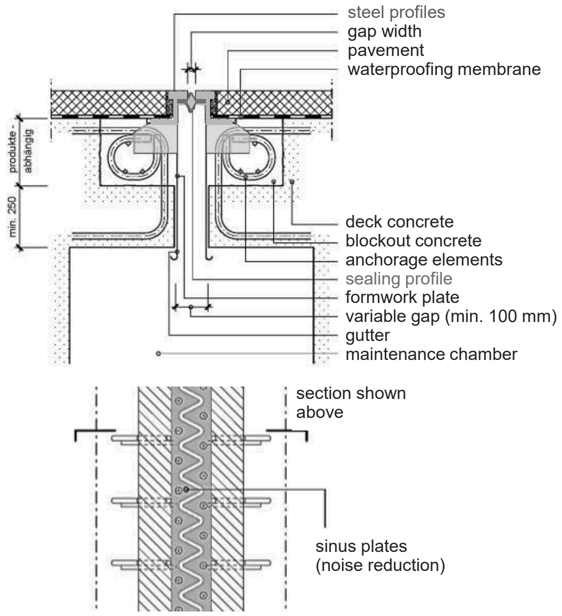
Single profile joint (“Fahrbahnübergang mit einem Dehnprofil”)
(“nosing joint”)

- are simple and robust (low risk of damage by snow plough)
- require relatively small blockouts only
- are theoretically watertight
- cause significant noise unless provided with sinus plates
- can accommodate multiaxial horizontal movements and small vertical offsets (the latter impairing user comfort and causing even more noise)
- typical movement capacity: 80 mm (100 mm with sinus plates)

→ economical and robust solution for small movements (including multiaxial horizontal movements)

The following should be observed:

- provide with sinus plates for noise attenuation
- even though theoretically watertight, provide controlled drainage (water evacuation duct) below



Figures / photos © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Support and articulation – Expansion joints

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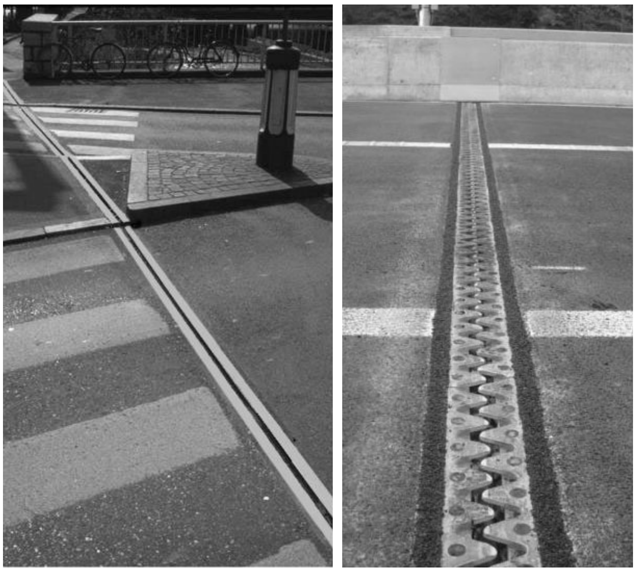


Figures / photos © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Support and articulation – Expansion joints

Cantilever (finger) joint (“Kragfingerübergang”)

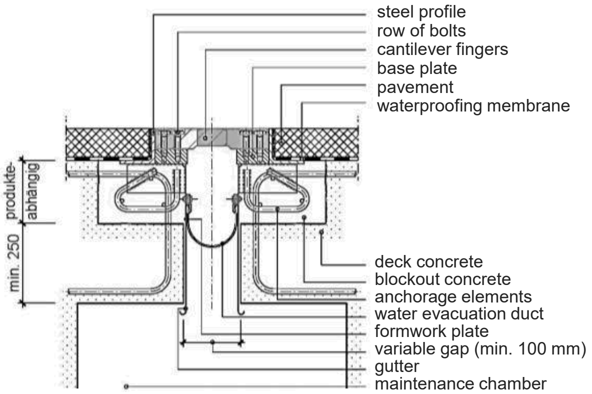
- are relatively simple but vulnerable by small vertical offsets (damage by snow plough)
- may cause severe traffic accidents if failing (e.g. due to fatigue) and put upright by traffic
- are not watertight → provide water evacuation duct below
- cause moderate noise
- can accommodate moderate multiaxial horizontal movements (with triangular “fingers”) but no vertical offset
- typical movement capacity: up to ≈ 400 mm

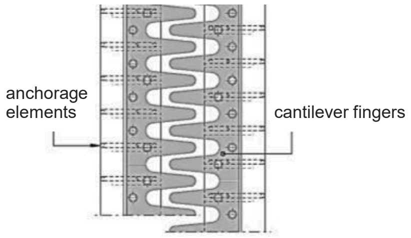
→ economical solution for moderate movements (including multiaxial horizontal movements)

→ but requires regular inspection to minimise risk of failure

The following should be observed:

- do not use unless vertical offsets can be excluded
- avoid in areas with regular snow plough traffic





Figures / photos © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Support and articulation – Expansion joints

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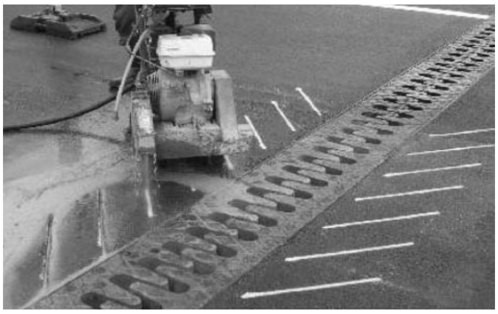


Figures / photos © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Support and articulation – Expansion joints

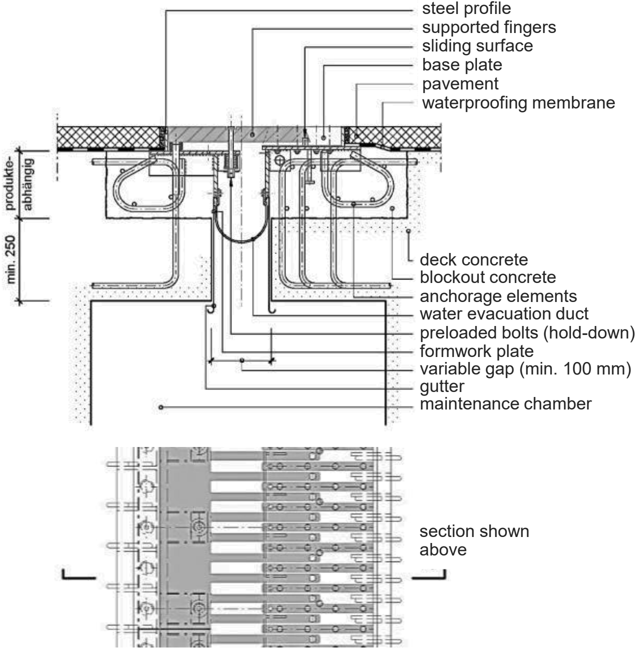
Supported finger joint (“Gleitfingerübergang”)

- are relatively complex mechanical devices
- are not watertight → provide water evacuation duct below
- cause moderate noise
- can only accommodate uniaxial horizontal movements in direction of fingers and no vertical offsets
- typical movement capacity: up to ≈ 800 mm

→ economical solution for large uniaxial movements

The following should be observed:

- avoid use if vertical offsets cannot be excluded
- do not use in areas with regular snow plough traffic
- avoid sliding finger joints without hold-down device (risk of accidents, see cantilever finger joint)



Figures / photos © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Support and articulation – Expansion joints

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Figures / photos © ASTRA RL 12004, Chapter 2 Expansion Joints (see there for German terms)

Support and articulation – Expansion joints

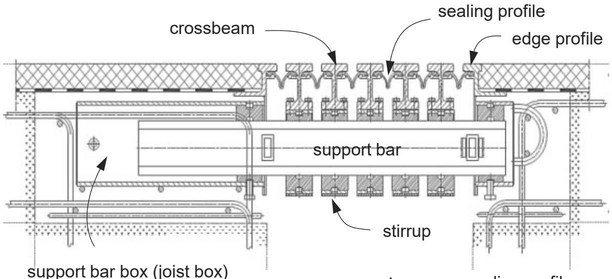
Modular joint (“Mehrzelliger Fahrbahnübergang”)

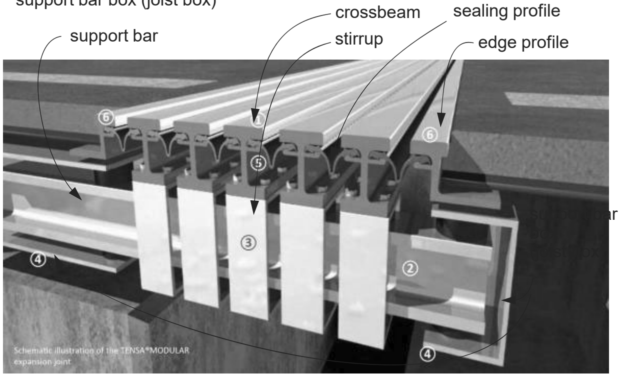
- are complex mechanical devices
- are theoretically watertight
- cause significant noise unless provided with sinus plates
- can accommodate large multiaxial horizontal movements and moderate vertical offsets
- typical movement capacity: 80 mm per sealing profile (100 mm with sinus plates), current record ≥ 24 profiles

→ adequate solution for large movements
(including multiaxial horizontal movements)
and for moderate vertical movements if vertical offsets cannot be excluded

The following should be observed:

- provide with sinus plates for noise attenuation
- even though theoretically watertight, provide controlled drainage (water evacuation duct) below
- products differ e.g. by steering system (avoid localisation of movement in weakest profile, photo on second slide)
- variants for seismic applications (lifeline structures) exist





Figures: © mageba

The figures show a modular joint without sinus plates. For variants with sinus plates (on top of crossbeams), see supplier documentation.

Support and articulation – Expansion joints

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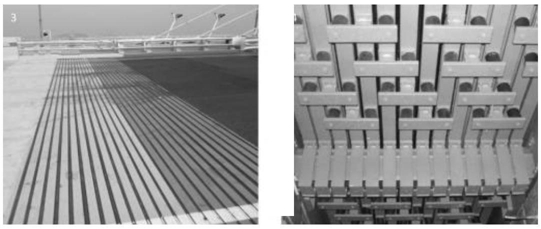

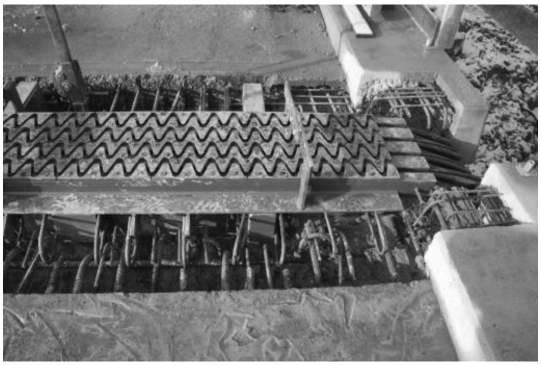

Photos:

Top Modular expansion joint of Run Yang bridge, 24 sealing profiles (1920 mm movement capacity) © mageba;

Bottom Modular expansion joint of Steinbachviadukt, four sealing profiles, provided with noise absorbing sinus plates (total movement capacity 400 mm) © dsp Ingenieure + Planer AG

Support and articulation – Expansion joints

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- variants for seismic applications (lifeline structures) exist

Video:

Movement components of a modular expansion joint © mageba;

Support and articulation – Expansion joints

Modular joint ("Mehrzelliger Fahrbahnübergang")

- are complex mechanical devices
- are theoretically watertight
- cause significant noise unless provided with sinus plates
- can accommodate large multiaxial horizontal movements and moderate vertical offsets
- typical movement capacity: 80 mm per sealing profile (100 mm with sinus plates), current record ≥ 26 profiles

→ adequate solution for large movements (including multiaxial horizontal movements) and for moderate vertical movements if vertical offsets cannot be excluded

The following should be observed:

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- even though theoretically watertight, provide controlled drainage (water evacuation duct) below
- products differ e.g. by steering system (avoid localisation of movement in weakest profile, photo on second slide)
- variants for seismic applications (lifeline structures) exist

Video:

Testing of a modular expansion joint for seismic applications © mageba;

Support and articulation

Jointed bridges – Bearing layout principles

Support and articulation – Bearing layout principles

Basic principles for choice of bearing layout

Always check first the feasibility of a (semi-) integral bridge.
If integral or semi-integral solutions are not possible, the following recommendations for jointed bridges apply:

- avoid girder joints in the span or over supports
  exception: long railway viaducts, see next slides
- avoid uplift (negative reactions), considering / optimising
  … proportion of spans (end span / typical span)
  … transverse spacing of bearings per support axis
  … torsion span
- minimise articulation of pier to girder connections
  … use flexible piers monolithically connected to girder
  … if not possible, use concrete hinges or fixed bearings
  … minimise longitudinally movable bearings on piers
- limit longitudinal restraint (no contradiction, see notes)
  … provide longitudinal fixity only at one abutment
- provide horizontal fixity at supports with high vertical reactions (e.g. monolithically connected piers); at abutments choose bearing with higher minimum vertical loads coexistent with maximum horizontal (see notes)

If longitudinal fixity at both abutments is possible, an integral bridge should be chosen. An exception are strongly curved steel bridges, where a monolithic connection to the abutments is complicated but longitudinally fixed connections at both abutments are possible, just like in integral bridges (absorbing expansion and contraction by radial movements, see integral bridges).

Guide or fixed bearings with low vertical loads may require special designs and are more expensive, therefore bearings with high vertical loads should be used for horizontal force transfer. Alternatively, guide bearing(s) may be used.

Photos:

Top Steinbachviadukt, dsp Ingenieure+Planer, 2012. Length 440 m, continuous girder with all piers monolithically connected (bearings and expansion joints at both abutments)

Bottom Innbrücke Vulpera, dsp Ingenieure+Planer, 2010. Monolithic connection of girder and pier, piers with high reactions used for longitudinal stabilisation

Support and articulation – Bearing layout principles

Basic principles for choice of bearing layout

An exception to the rule of avoiding girder joints are long railway viaducts, since rail expansion devices are highly complex and very expensive, yet only available up to a limited length.

Two different solutions (illustrated on some recent examples of high-speed rail viaducts on the following slides) can be distinguished:

- avoid rail expansion devices
  → limit movement length to $l_{mov} \approx 90$ m by bridge expansion devices
  (value of l_{mov} by experience or track-bridge interaction analysis)
- exploit maximum movement capacity of rail expansion devices
  → e.g. for Spanish AVE max. girder end movement ≈ 1200 mm
  movement length $l_{mov} \approx 1200$ m (concrete) …1600 m (composite)

In many cases, avoiding rail expansion devices is preferred, since these devices are very expensive and require regular maintenance. However, this benefit may be outweighed by the less efficient structural system caused by the bridge expansion, both for vertical loads (no continuity at joints) as well as for horizontal loads (full braking/traction forces on each 90 m bridge segment requiring massive piers). In soft soil and/or challenging conditions for pier placement, providing a rail expansion device may thus be preferable economically and aesthetically.

Top photo: Unstruttalbrücke, Erfurt-Leipzig/Halle (Schlaich Bergermann Partner, 2012) © Jan Wojtas, dpa

Bottom photo: Viaducto de Archidona, Granada-Malaga (IDEAM, 2012) © IDEAM

Support and articulation – Bearing layout principles

Gänsebachtalbrücke, Erfurt-Leipzig/Halle (Schlaich Bergermann Partner, 2012):

- double track high speed railway bridge, ballastless track
- prestressed concrete girder
- total length 1’001 m, height ca. 20 m
- main span 24.5 m, girder depth 3 m
- 10 fully monolithic sections:
  52.5 + 8·112 + 52.5 m
- no rail expansion devices
- stabilised longitudinally by integral abutments and 10-12 m wide stiff bents, at centre of 112 m sections
- stabilised transversely by abutments and frames at bridge expansion joints (i.e. between sections, which are connected in transverse direction to avoid horizontal offsets)

Photo © Deutsche Bahn AG / Hannes Frank

Support and articulation – Bearing layout principles

Photo © Bundesstiftung Baukultur (left) / Deutsche Bahn AG (right)

Support and articulation – Bearing layout principles

Unstruttalbrücke, Erfurt-Leipzig/Halle
(Schlaich Bergermann Partner, 2012):

- double track high speed railway bridge, ballastless track
- prestressed concrete girder
- total length 2’668 m, height ca. 50 m
- main span 58 m, arch span 108 m, girder depth 5.69 m
- 6 fully monolithic sections:
  174 + 4·580 + 174 m
- stabilised horizontally by abutments and arches at centre of 580 m sections
- bridge expansion joints and rail expansion devices between sections (movement length 580 m)
- four bridge bearings only (two per abutments)

Photo © Peter Gercke, dpa

Support and articulation – Bearing layout principles

Photo © Deutsche Bahn AG (construction) / Wikiwand creative commons (separating pier)

Support and articulation – Bearing layout principles

Photo © Peter Gercke, dpa

Support and articulation – Bearing layout principles

The standard design for similar viaducts was much less elegant and maintenance-free, as illustrated by the Ilmtalbrücke, Nürnberg-Erfurt (K+S Ingenieur-Consult, 2011), in a quite similar location as the Unstruttalbrücke:

- double track high speed railway bridge, ballastless track
- prestressed concrete girder
- total length 1’681 m, height ca. 50 m
- main span 58 m, arch spans 175 m / 155 m / 125 m, girder depth 5.90 m
- 4 sections with continuous girder supported on bearings:
  174 + 4·580 + 174 m
- stabilised horizontally by abutments and arches at centre of 580 m sections
- bridge expansion joints and rail track expansion devices between sections
- girder launched from abutments except central section → bearings used for construction process

Photo © Wikipedia creative commons

Support and articulation – Bearing layout principles

Viaducto de Archidona, Granada-Malaga (IDEAM, F. Millanes, 2012):

- double track high speed railway bridge, ballasted track
- steel-concrete composite girder with double composite action
- total length 3’150 m, height ca. 25 m
- continuous girder over 3’150 m, spans 35 + 29·50 + 2·65 + 30·50 + 35 m
- girder depth 3.40 m
- stabilised longitudinally by triangular bent at the centre of the 3’150 m
- stabilised transversely at each pier (two multiaxial sliding bearings and a shear key on top of each pier)
- bridge expansion joints and rail track expansion devices at both abutments, movement length 1’600 m / 1’550 m

Support and articulation – Bearing layout principles

Support and articulation – Bearing layout principles

Basic principles for choice of bearing layout

After this excursion into the exception to the rule of avoiding girder joints (long railway viaducts), remember the main principles for the choice of the bearing layout:

- check feasibility of (semi-) integral bridge
- avoid girder joints (except in long railway viaducts)
- avoid uplift
- minimise articulation of pier to girder connections
- limit longitudinal restraint
- provide horizontal fixity at supports with high vertical reactions

Photos:

Top Steinbachviadukt, dsp Ingenieure+Planer, 2012. Length 440 m, continuous girder with all piers monolithically connected (bearings and expansion joints at both abutments)

Bottom Innbrücke Vulpera, dsp Ingenieure+Planer, 2010. Monolithic connection of girder and pier, piers with high reactions used for longitudinal stabilisation

© dsp Ingenieure+Planer

Support and articulation – Bearing layout principles

Basic principles for choice of bearing layout (continued)

Further aspects to be considered (see figures) are:

- movable bridge bearings are usually arranged horizontally, but the road / railway line has a longitudinal gradient

→ vertical offset caused by horizontal girder end movements

→ at large movements and/or slopes :
  … use expansion joint that accommodates vertical offsets
  … or arrange bearings parallel to road alignment
  (in railway bridges, only possible solution)

- position expansion joints close to the support axis to minimise vertical offsets caused by girder end rotations

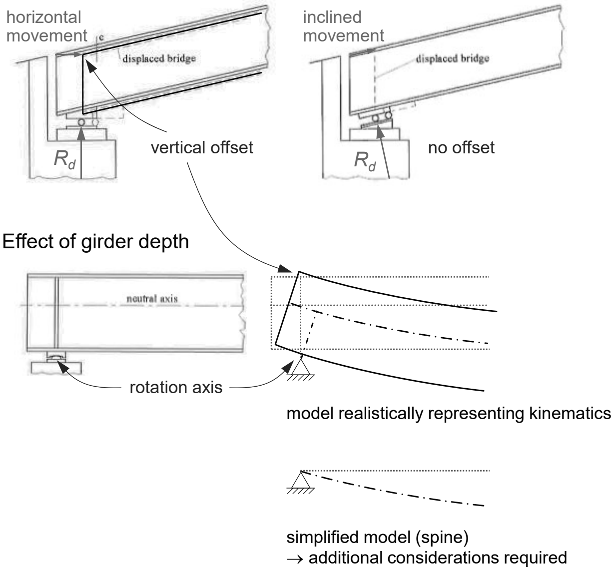
- movable bearings cause horizontal reactions (friction, elasticity of deformed elastomeric bearing, …)

→ account for in the design of substructure

- Expansion joints and movable bearings are usually installed with an offset (more movement capacity for girder contraction than expansion)

→ consider installation temperature when choosing offset

Effect of longitudinal gradient (slope)



Illustrations: Adapted from G. Ramberger, Bearings and expansion joints for bridges, IABSE SED No 6, 2002

Support and articulation – Bearing layout principles

Basic principles for choice of bearing layout (continued)

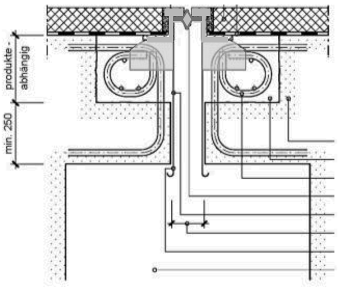
Further aspects to be considered (continued):

- single profile expansion joints (nosing joints) are
  … inexpensive
  … much more robust than other expansion joints
  … have a movement capacity of $\Delta u_{spj} = 80\ldots100$ mm
  (80 mm without, 100 mm with sinus plates)
  → concepts using only single profile expansion joints preferred

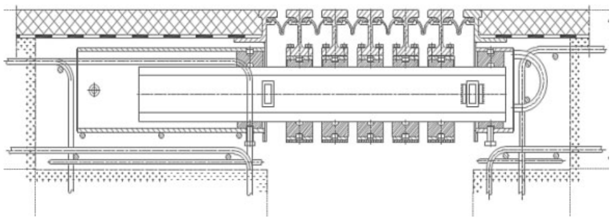
→ if design movements for entire girder length are less than Δu_{spj}
  → fixity at one abutment (usually less high abutment)
  → single profile expansion joint at other abutment

→ if design movement for entire girder length is between Δu_{spj} and $2\cdot\Delta u_{spj}$
  → longitudinal stabilisation by piers (with fixed point near middle of bridge length)
  → single profile expansion joint at both abutments

Single profile expansion joint



Modular expansion joint

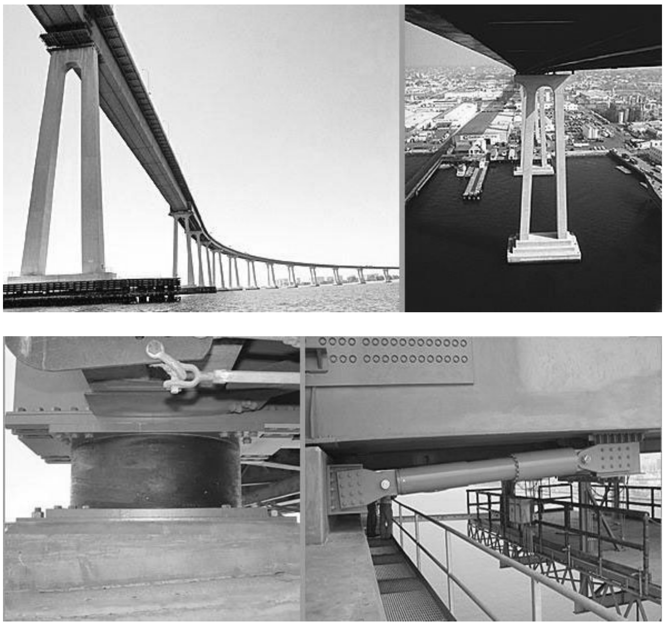


Support and articulation – Bearing layout principles

Basic principles for choice of bearing layout (continued)

In sites with high seismicity, different strategies are possible, considering the following aspects:

- Integral bridges (e.g. frames) are generally well suited for seismic regions, but
  … relatively high seismic loads (stiff system)
  … large forces may be induced to the bridge by integral abutments (the abutments move the bridge)
  → may be problematic in long bridges
- Horizontal seismic loads may be significantly reduced by providing longitudinal fixity at a flexible pier, rather than an abutment (low frequency) but
  … movements under non-seismic horizontal forces (braking) may become critical
- For very high seismicity, elastomeric bearings with high damping (lead rubber bearings) or special (spherical) bearings with large movement capacity may be used to achieve a base isolation.



In some cases, large movements need to be accommodated due to temperature, shrinkage and creep, but at the same time, large horizontal forces should be resisted (braking, earthquakes).

An example are long high speed rail viaducts where the horizontal forces due to braking or earthquakes cannot be resisted by the piers (e.g. since girder movements are too large, requiring sliding bearings), nor by one abutment alone.

In such cases, hydraulic devices may be used, which enable slow movements to occur without significant restraint, but essentially provide a full restraint against fast movements (positive and negative chambers of actuator connected with valve) limiting oil flow. This allows sharing “fast” horizontal forces among the abutments or several piers without impeding girder expansion or contraction. Similar devices are also used for seismic retrofitting bridges.

Since these devices are expensive and require regular maintenance, they should be avoided if possible.

Photo: Coronado Bridge, seismic retrofit © Forrell Elsesser Structural Engineers
https://forell.com/projects/transportation/coronado-bay-bridge-seismic-retrofit/

Support and articulation

Jointed bridges – Bearing layout examples

Support and articulation – Bearing layout examples

Examples: Simply supported girder

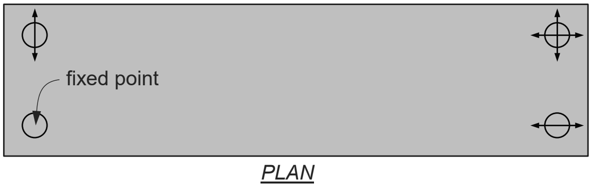
In a simply supported girder, longitudinal fixity must be provided at an abutment.

The figure shows an «obvious» solution:

- longitudinal fixity provided by both bearings at left abutment
- transverse fixity provided by one bearing per abutment
  This bearing layout theoretically
- Avoids restraint due to expansion and contraction
- provides statically indeterminate horizontal support (clamped at left abutment)
- allows sharing longitudinal support reactions among two bearings

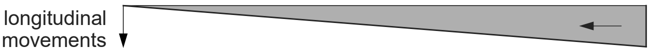
While this would be advantageous, this bearing layout should be avoided due to tolerances in uniaxial bearings, see next slide

Obvious solution – not recommended (yet often used …)



Vertical static system

Horizontal static system (clamped… but tolerances?)



Torsional support system (statically indeterminate)

Support and articulation – Bearing layout examples

Examples: Simply supported girder

The guides of uniaxial bearings usually have several millimetres of play due to tolerances

→ unclear if clamping at left abutment can be activated (girder stiff in transverse direction)

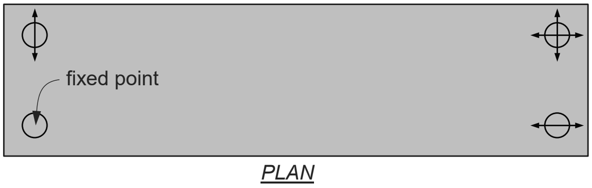
→ longitudinal forces will act on one bearing only, until it deforms considerably, but usual bearings do not provide sufficient ductility for relevant redistribution

→ layout to be avoided (though often used and shown in many textbooks)

Further remark: As in all usual solutions with four bearings (following slides), the support for vertical forces is statically indeterminate (3 vertical supports would be sufficient)

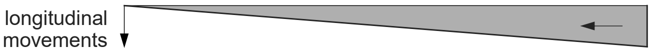
→ relevant for steel and prefabricated girders lifted in (precise levelling of supports required unless the torsional stiffness is small)

Obvious solution – not recommended (yet often used …)



Vertical static system

Horizontal static system (clamped… but tolerances?)



Torsional support system (statically indeterminate)

Support and articulation – Bearing layout examples

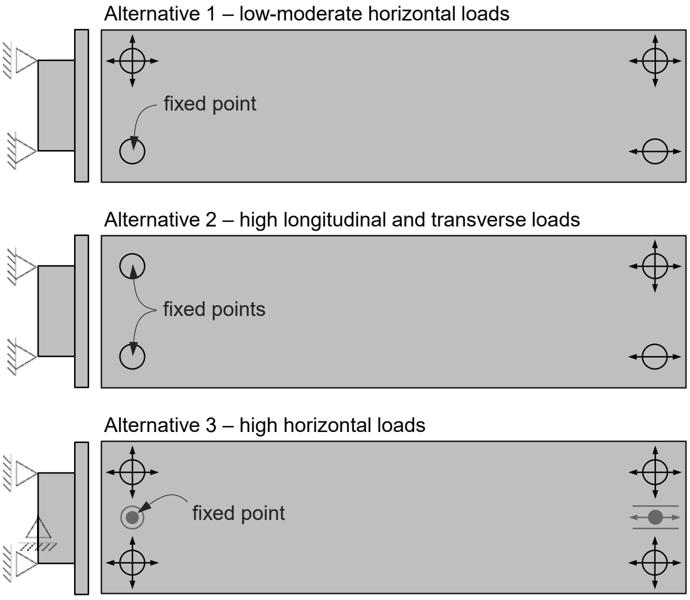
Examples: Simply supported girder

The figure shows three alternatives to the «obvious» solution on the previous slides:

(1) longitudinal fixity provided by one bearing at left abutment, transverse fixity by one bearing per abutment
  → statically determinate horizontal support
  → limited capacity for longitudinal forces

(2) Longitudinal and transverse fixity provided by two bearings on left abutment, transverse fixity by one bearing on right abutment
  → higher capacity for longitudinal forces
  → frame action in transverse direction to be considered at left abutment (higher transverse reactions)

(3) horizontal fixity provided entirely by separate guide bearings
  → suitable for high horizontal forces even for small vertical reactions (e.g. due to torsion)
  → more expensive


Alternative 1 – low-moderate horizontal loads

Alternative 2 – high longitudinal and transverse loads

Alternative 3 – high horizontal loads

In alternative 2, horizontal fixity may also be provided by two guide bearings on the right abutment (rather than only one), if no support diaphragm is provided (i.e., cross-section will deform until both bearings are activated and frame action develops.

Support and articulation – Bearing layout examples

Examples: Continuous girder

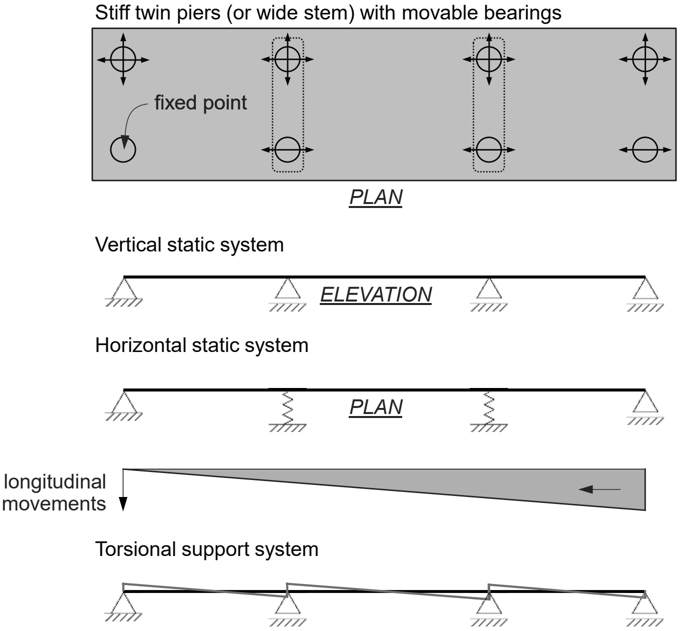
Stiff twin piers or stems with movable bearings

In continuous girders, longitudinal fixity may be provided by the piers or at an abutment.

The figure shows a solution for a girder supported on bearings positioned on top of stiff twin piers (or stems):

- longitudinal fixity provided at left abutment
- transverse fixity provided by one bearing per vertical support axis
- torsional support provided at abutments and piers

→ feasible solution, advantages / weak points:
… many bearings
… many stiff piers or massive stems
… large movements to be accommodated at right abutment
… short torsion span



Stiff twin piers (or wide stem) with movable bearings

Vertical static system

Horizontal static system

Torsional support system

More examples of bearing layouts can be found in the Support and Articulation Annex online.

Support and articulation – Bearing layout examples

Examples: Continuous girder

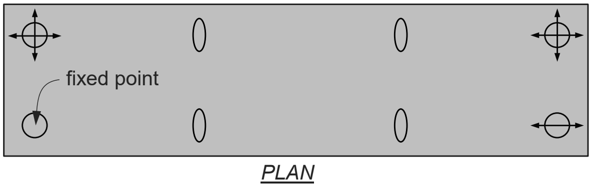
Longitudinally slender twin piers, monolithic connection or fixed bearings

The figure shows a solution for a girder supported on slender twin piers, monolithically connected to the girder (or via fixed bearings / concrete hinges)

- longitudinal fixity provided at left abutment
- small longitudinal restraint (pier stiffness)
- transverse fixity provided by piers and one bearing per abutment
- torsional support provided at abutments and piers

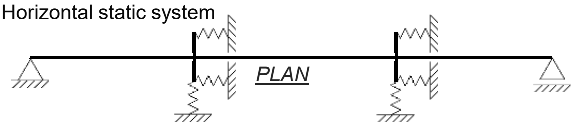
→ feasible solution, advantages / weak points:
… bearings only at abutments
… many piers (but slender)
… large movements to be accommodated at right abutment
… short torsion span

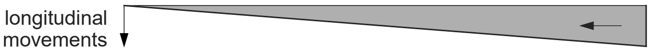
Longitudinally slender twin piers, monolithic or fixed bearings



Vertical static system

Horizontal static system





Torsional support system

Support and articulation – Bearing layout examples

Examples: Continuous girder

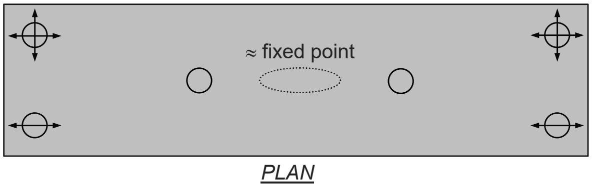
Single piers longitudinally stabilising the girder

The figure shows a solution for a girder supported on single piers, monolithically connected to the girder (or via fixed bearings / concrete hinges)

- longitudinal fixity provided by piers
- small longitudinal restraint (pier stiffness)
- transverse fixity provided by piers and one bearing per abutment
- torsional support provided at abutments only (plus transverse frame action, see notes)

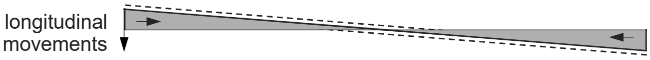
→ feasible solution, advantages / weak points:
… bearings only at abutments
… few piers, elegant solution but
higher demand on pier foundations
… movements split among abutments
… uncertainty in position of fixed points
… long torsion span → risk of uplift at
abutments (see next slides)

Single piers, monolithic or fixed bearings



Vertical static system

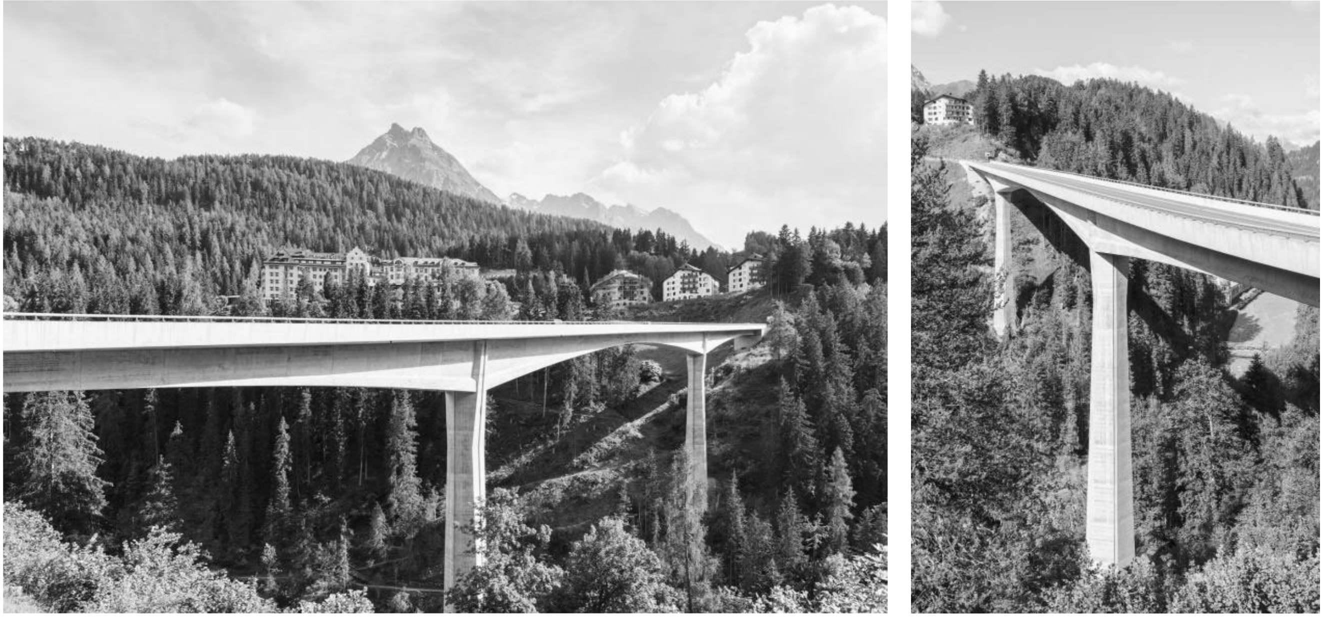
Horizontal static system



Torsional support system (shown for case of bearings on piers)

The notes on the previous side apply here as well – see following slide for example.

Support and articulation – Bearing layout examples



Innbrücke Vulpera, dsp (2010). Support and articulation see previous slide. Photo © dsp Ingenieure + Planer

Support and articulation – Bearing layout examples

Examples: Continuous girder

If single piers are used, torsional moments at the abutments are higher and hence uplift may occur

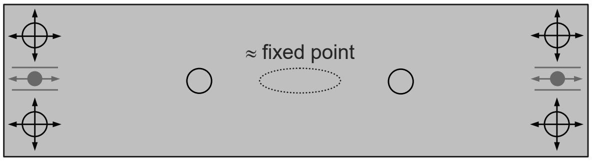
→ avoid if possible by changing the bearing layout, see «basic principles for choice of bearing layout» for options)

- even without uplift, the vertical support reactions may not be sufficient to transfer horizontal loads with conventional bearings

→ guide bearings may be required, as illustrated in the figures on the slide

Longitudinally slender single piers, monolithic or fixed bearings

Single piers, monolithic or fixed bearings



Horizontal static system (same as without guide bearings)

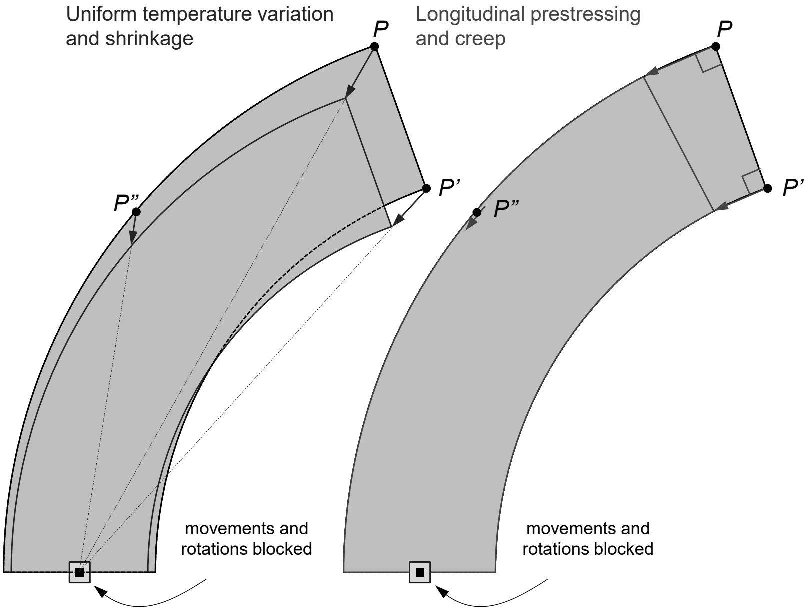
Support and articulation – Curved bridge kinematics

Examples: Curved bridges (kinematics)

Two types of girder deformations occur:

- longitudinal prestressing and creep
  → axial deformation
  → girder shortens along ist axis
  → radius of curvature remains unchanged
  → tangential movements at opposite bridge end
- uniform temperature variation and shrinkage
  → uniform (3D) deformation
  → girder is «scaled»
  → radius of curvature changes
  → “radial” movements in direction of fixed point

In straight bridges, the direction of these movements (nearly) coincide. In strongly curved bridges, the differences are significant.



More information on curved support and articulation layouts can be found in Chapter 8.4 (Curved Bridges) and in the online Support & Articulation Annex.

Support and articulation – Curved bridge kinematics

Examples: Curved bridges (kinematics)

By allowing a rotation around the fixed point (usually at one abutment), it is possible to obtain the same direction of movement, due to

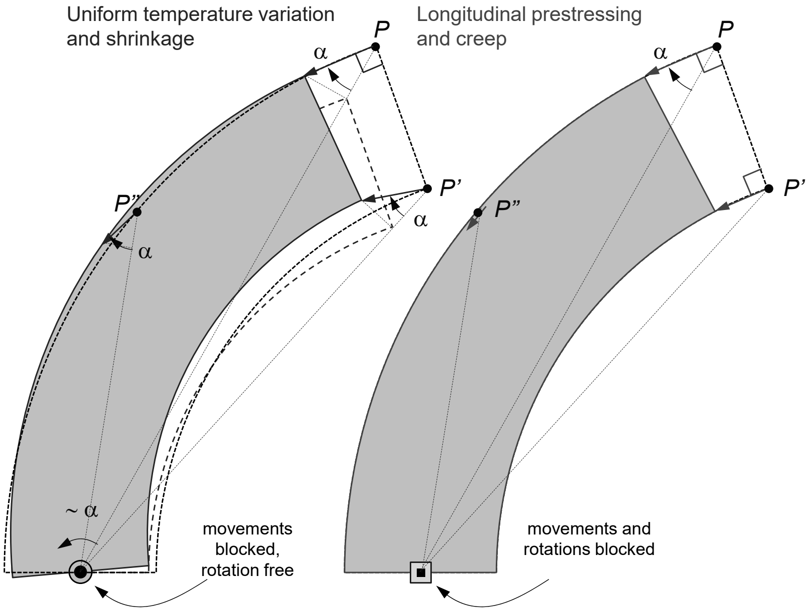
- temperature and shrinkage and
- longitudinal prestressing and creep

for one specific point *P* of a curved girder. Typically, the point P is chosen at a uniaxial sliding bearing at the opposite abutment, moving tangentially to the girder axis (standard expansion joint width can be used), see figure on the right.

All other points (e.g. P’, P’’) still move in different directions due to temperature and shrinkage and longitudinal prestressing and creep, respectively.

→ only one uniaxially movable bearing (other than the fixed point) possible for horizontally restraint-free support of curved bridges

→ corresponds to isostatic support in plan



Apart from the solution shown in the slide (uniaxial bearing at opposite abutment moving tangentially to bridge axis), an infinite number of other arrangements avoiding horizontal restraint exist (just need to provide isostatic support in plan).

For example, a solution found in some textbooks consists in orienting the uniaxial bearing at the opposite abutment radially (i.e., rotation α in opposite direction than shown on slide, and proportional to movements due to prestressing and creep rather than temperature and shrinkage). However, this requires a skew opening expansion joint and is rarely used in practice.

Support and articulation – Bearing layout examples

Examples: Curved simply supported girder

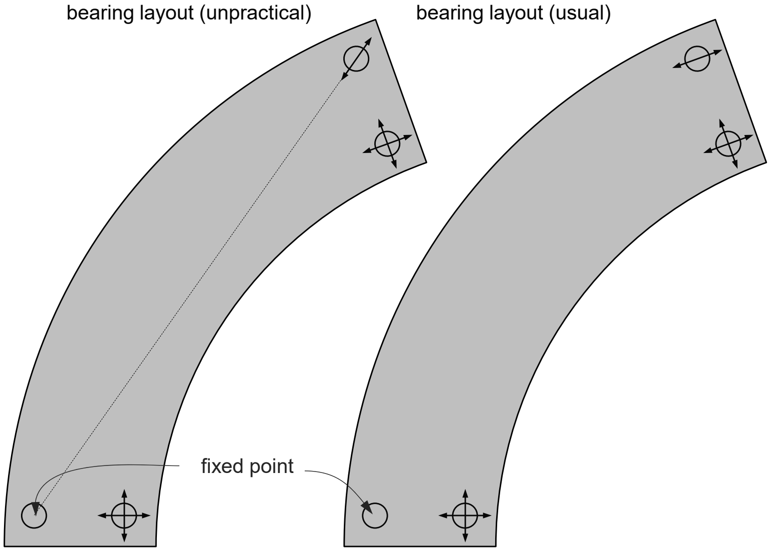
In simply supported curved bridges, horizontal fixity must be provided at an abutment:

- at the other abutment, a tangential bearing layout is preferable (standard expansion joint)
- horizontally fixed bearings are preferably positioned at the outside (larger support reaction)

Regarding longitudinal and transverse fixity see straight simply supported bridges (slide with possible alternatives 1-3).

Horizontal restraint-free radial bearing layout (unpractical)

Horizontal restraint-free tangential bearing layout (usual)



Support and articulation – Bearing layout examples

Examples: Curved continuous girder

Monolithically connected piers longitudinally stabilising the girder

As for straight continuous girders, small restraint forces caused by monolithically (or via fixed bearings or concrete hinges) connected piers can often be accepted.

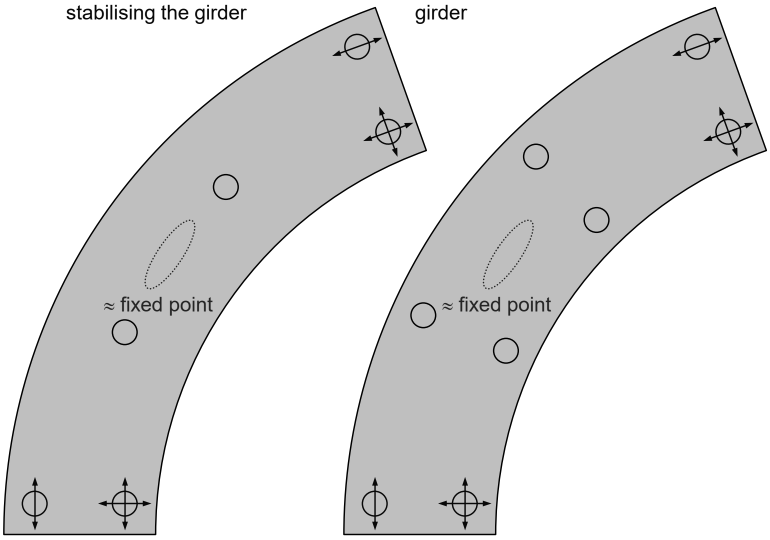
On this slide, solutions where the piers provide longitudinal fixity are shown.

Compared to straight bridges, uplift is more likely due to the curvature in plan, particularly in the single piers solution (→ guide bearings)

Further advantages and drawbacks see straight girders.

Single monolithically connected piers longitudinally stabilising the girder

Twin monolithically connected piers longitudinally stabilising the girder



Support and articulation – Bearing layout examples

Examples: Curved continuous girder

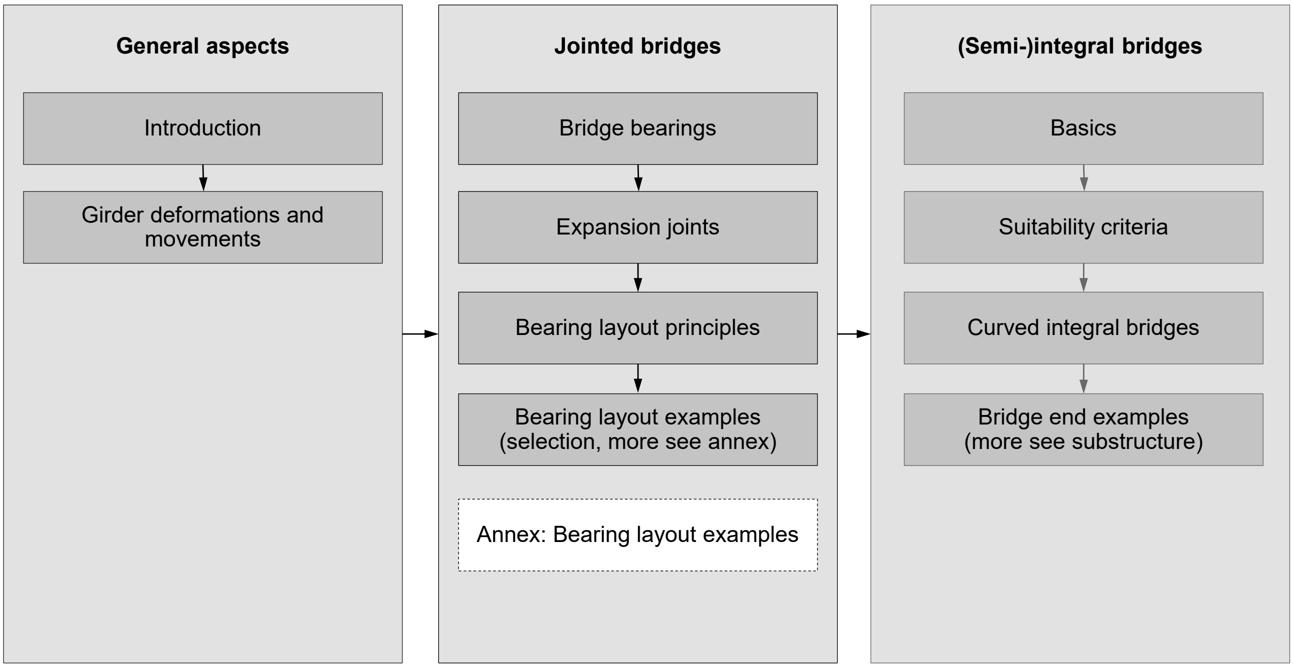
Designers sometimes hesitate to use single piers in curved bridges since they anticipate that

- due to the longer torsional span (compared to twin pier support layouts)
- the torques M_y/r caused by curvature
- will result in ~~disproportional torsional~~ moments

However, in a continuous girder, the positive and negative torques (caused by positive and negative bending moments) largely compensate, such that only little torsion is resisted by piers providing torsional support anyway. Solutions with single piers are therefore perfectly feasible in long curved bridges.

Further details see curved bridges.

Photos: Zurich Airport, OPC “Spinnenbrücke”), dsp Ingenieure+Planer AG.



General aspects

Introduction

Girder deformations and movements

Jointed bridges

Bridge bearings

Expansion joints

Bearing layout principles

Bearing layout examples (selection, more see annex)

Annex: Bearing layout examples

(Semi-)integral bridges

Basics

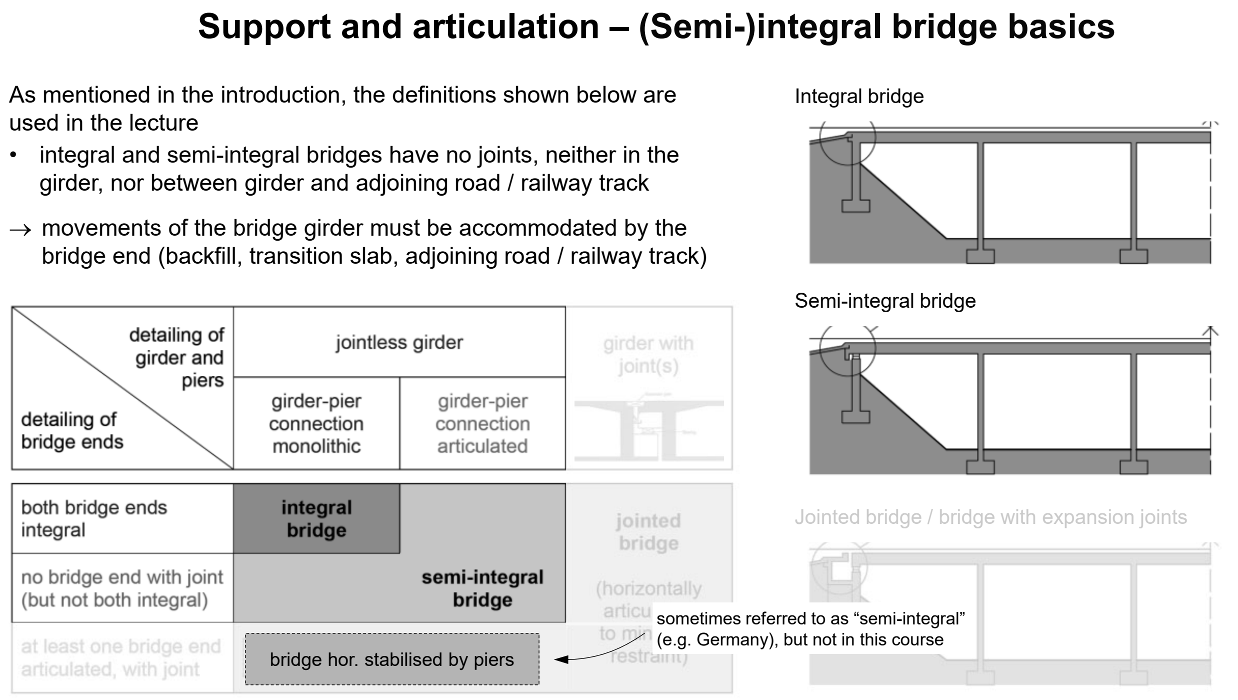
Suitability criteria

Curved integral bridges

Bridge end examples (more see substructure)

Support and articulation

Integral and semi-integral bridges – Basics



Support and articulation – (Semi-)integral bridge basics

As mentioned in the introduction, the definitions shown below are used in the lecture

- integral and semi-integral bridges have no joints, neither in the girder, nor between girder and adjoining road / railway track

→ movements of the bridge girder must be accommodated by the bridge end (backfill, transition slab, adjoining road / railway track)

detailing of girder and piers detailing of bridge ends	jointless girder		girder with joint(s)
	girder-pier connection monolithic	girder-pier connection articulated	
both bridge ends integral	**integral bridge**	**semi-integral bridge**	**jointed bridge** (horizontally articu to min restraint)
no bridge end with joint (but not both integral)	**semi-integral bridge**	**semi-integral bridge**	
at least one bridge end articulated, with joint	bridge hor. stabilised by piers		

sometimes referred to as “semi-integral” (e.g. Germany), but not in this course

Integral bridge

Semi-integral bridge

Jointed bridge / bridge with expansion joints

Note that the terminology used for integral and semi-integral bridges varies considerably. For example, in a bridge horizontally stabilised by the piers, but with expansion joints at both bridge ends, is called “semi-integral” or even “integral” in some textbooks if the piers are monolithically connected to the girder.

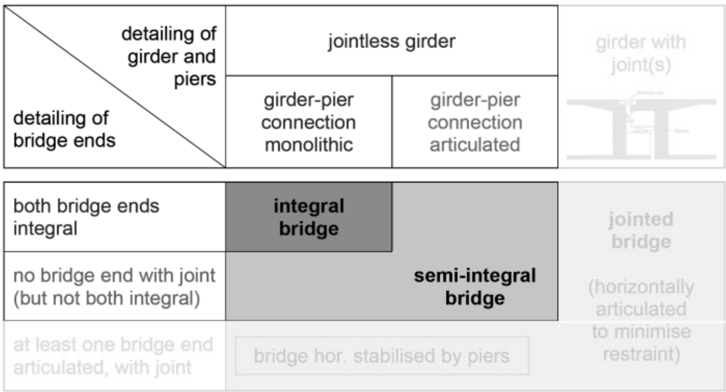
Figures: Astra Richtlinie 12004 Konstruktive Einzelheiten von Brücken, Fig. 1.1 (translated to English and adapted)

Support and articulation – (Semi-)integral bridge basics

As mentioned in the introduction, the definitions shown below are used in the lecture

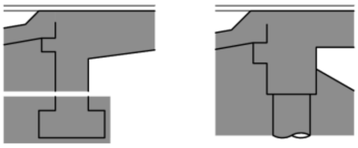
- integral and semi-integral bridges have no joints, neither in the girder, nor between girder and adjoining road / railway track

→ movements of the bridge girder must be accommodated by the bridge end (backfill, transition slab, adjoining road / railway track)

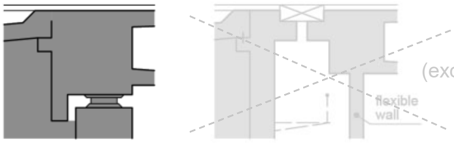


detailing of girder and piers / detailing of bridge ends	jointless girder		girder with joint(s)
	girder-pier connection monolithic	girder-pier connection articulated	
both bridge ends integral	**integral bridge**	**semi-integral bridge**	**jointed bridge** (horizontally articulated to minimise restraint)
no bridge end with joint (but not both integral)			
at least one bridge end articulated, with joint	bridge hor. stabilised by piers		

Integral bridge ends (neither expansion joint nor bearing)



Semi-integral bridge ends (bearing only)



(exception)

Jointed bridge ends (with expansion joint and bearing)

Figures: Astra Richtlinie 12004 Konstruktive Einzelheiten von Brücken, Fig. 1.1 (translated to English and adapted)

Support and articulation – (Semi-)integral bridge basics

If the bridge ends of a straight (semi-)integral bridge were perfectly rigid:

- deformations Δ_0 of the girder would be fully restrained
- huge normal forces N_0 would result

→ normal bridge ends cannot resist such high forces (particularly in tension) without significant movements (the abutment is stiff, but subsoil and backfill are not)

→ modelling rigid bridge ends is completely unrealistic

The behaviour can usually be reasonably approximated by using elastic springs with a flexibility c_f [m/kN], where the bridge ends are typically much more flexible than the bridge girder:

$$c_{f1} + c_{f2} \gg \frac{l}{EA} \quad \text{[m/kN]}$$

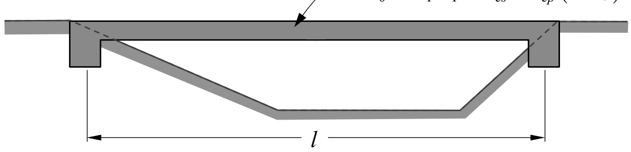
→ restraint forces N are much smaller than those for full restraint (usually less than 10% of N_0)

→ almost the full, free (unrestrained) deformations Δ_0 of the girder occur and have to be accommodated by the bridge ends (horizontal movements Δ_h)

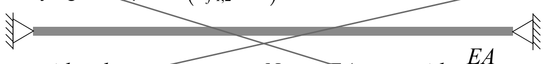
Integral bridge (schematic)

$$EA$$

$$\varepsilon_0 = \alpha_T \Delta_T + \varepsilon_{cs} + \varepsilon_{cp}(1+\varphi)$$



Horizontally rigid supports $(c_{f1,2} = 0)$ unrealistic



$\Delta l_0 = l \cdot \varepsilon_0$ (free deformation)

$N_0 = -EA \cdot \varepsilon_0 = -\Delta l_0 \cdot \frac{EA}{l}$ (full restraint)

Horizontally flexible supports $(c_{f1,2} \gg l/EA)$

$$\Delta l = \Delta l_0 \cdot \left(\frac{c_{f1} + c_{f2}}{c_{f1} + c_{f2} + \frac{l}{EA}} \right) \approx \Delta l_0 \qquad N = N_0 \cdot \left(\frac{1}{1 + \frac{c_{f1} + c_{f2}}{l/EA}} \right) \ll N_0$$

As an order of magnitude, a fully restrained contraction of $\varepsilon_0 = -1 \cdot 10^{-3}$ would correspond to a tensile normal force of about 150 MN (!) in a 10 m wide concrete bridge girder ($A_c \approx 5$ m^2, $E_c \approx 30$ GPa).

Since the tensile stresses would amount to $\sigma_c = E_c \varepsilon_0 \approx 30$ MPa (ca. 10 MPa long term), the girder would certainly crack. But even after cracking, the tensile forces would be much too high to be resisted by a normal bridge abutment without significant movements (the cracking load is higher than the resistance of normal abutments). Hence, the assumption of “rigid” abutments is completely unrealistic, except in very few cases (such as a bridge that is fully monolithic with long tunnels at both ends).

Support and articulation – (Semi-)integral bridge basics

The most unfavourable value of the restraint forces N (though much smaller than N_0) must be accounted for in the design of the bridge girder

→ design for bending + axial tension (at max. contraction)

As in jointed bridges, the bridge ends must accommodate the movements of the girder, which are caused by :

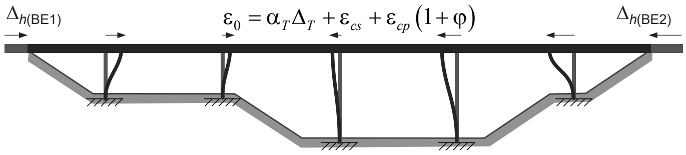
- expansion and contraction of the girder (temperature, shrinkage, prestressing, creep)
- horizontal (and sometimes vertical) loads

These bridge end movements Δ_h depend on many parameters subject to uncertainty, particularly

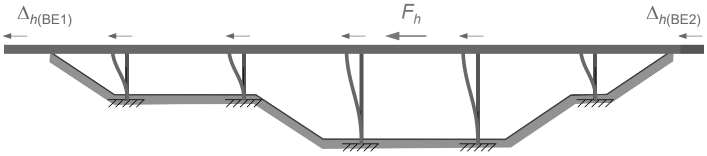
- cracking of piers and abutments
- soil–structure interaction

Generally, a sensitivity analysis using upper and lower bound values of soil parameters should be carried out, particularly in order to capture their influence on the position of the fixed point (centre of movement) for girder deformations.

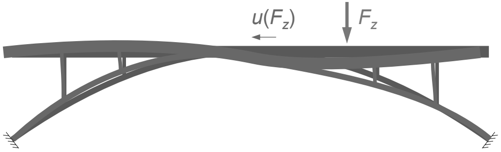
Movements due to girder contraction (schematic, integral bridge)



Movements due to horizontal load (schematic, integral bridge)



Movements due to vertical load (schematic, integral bridge)



Note:

While restraint can usually be neglected when designing bridge girders with sufficient rotation capacity (such as concrete girders with $x/d < 0.35$), the restraint forces N need to be accounted for since the expansion of the bridge girder in case of a bending failure (even more so in case of a shear failure) is insufficient to compensate the restraint (tensile forces are only slightly reduced).

Support and articulation – (Semi-)integral bridge basics

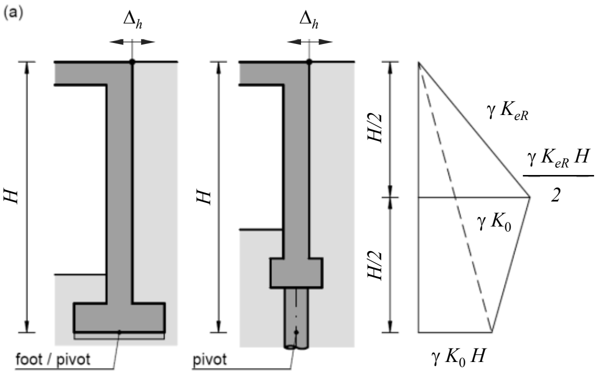
The movements of the bridge ends are

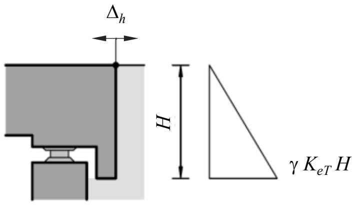
- partly monotonic (shrinkage, prestressing, creep)
- partly cyclic (temperature)

The abutment walls move with the girder, which in turn imposes them to the backfill, causing so-called strain-ratcheting and hence

→ significantly higher earth pressures on the abutment wall (see illustrations on right side), to be accounted in the dimensioning of abutment and girder

→ settlements of the backfill and pavement cracks if the movements are large (see next slide)





$$K_{eR} \approx K_0 + K_p \left(\frac{33 \cdot \Delta_h}{H} \right)^{0.6} \leq K_p$$

$$K_{eT} \approx K_0 + K_p \left(\frac{40 \cdot \Delta_h}{H} \right)^{0.4} \leq K_p$$

The enhanced earth pressures need to be accounted for in the dimensioning of the abutment and the girder (compression).

In the dimensioning of the bridge girder, the tensile restraint forces occurring at maximum contraction also need to be accounted for (dimensioning for bending and axial tension). Unlike restraint caused by other effects (such as differential settlements), the axial restraint forces cannot be neglected even in a ductile structure, since the elongations of the girder caused by a bending failure are not sufficient to significantly reduce the axial restraint forces .

Illustrations: ASTRA Richtlinie 12004

Support and articulation – (Semi-)integral bridge basics

In long integral bridges, the movements of the bridge ends are large and hence

- settlements of the backfill and pavement cracks must generally be expected
- the locations where pavement cracks will occur cannot be accurately predicted

→ pavement cracks can only partly be avoided by saw-cutting the pavement or flexible plug joints

→ certain pavement repair works must therefore always be expected in this type of structure

Photos: Landwasserbrücke Solas, Filisur (GR), taken from Kaufmann, W. and Buchheister J., Experiences with long integral and semi-integral bridges, AGB Report Nr. 697, 2016

Support and articulation – (Semi-)integral bridge basics

Hence, the movements Δ_h of the bridge ends are obviously the pertinent criterion for the suitability of integral and semi-integral bridge ends

- first proposed in ASTRA guideline 12004 (2010) (limit 20…30 mm, see following slides)
- part of current draft Annex A2 to EN1990 (limit 30 mm)

Earlier guidelines instead used the movement length as criterion. However, this neglects that:

- girder deformations differ significantly

→ longer composite integral bridges possible

- girder deformations are much smaller in existing concrete bridges (shrinkage + creep have decayed)

→ in bridge rehabilitations existing expansion joints can often be eliminated (semi-integral abutments)

- curved bridges absorb girder deformations by radial movements (see curved integral bridges)

Photos:

Top Sunnibergbrücke Klosters (Christian Menn 1998/2006), integral length 526 m © Tiefbauamt Graubünden;

Bottom Vorderrheinbrücke Reichenau (1986), L = 68 m, semi-integral © W. Kaufmann

Support and articulation – (Semi-)integral bridge basics

Nevertheless, integral and semi-integral structures are appropriate and economic in many cases, since they offer a number of advantages:

→ lower construction costs
  … no maintenance chamber
  … no expansion joint
  … no separate drainage

→ lower maintenance costs (pavement repairs vs. maintenance of expansion joints) with plannable, short interventions only

→ less restricted ratios of side span / interior span (uplift less critical)

→ longer or more slender end spans possible (frame action of integral abutment, see photo)

→ noise reduction and enhanced user comfort (no discontinuity in pavement, smoother ride)

→ structural redundancy (robustness)

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

Support and articulation

Integral and semi-integral bridges – Suitability criteria

Support and articulation – (Semi-)integral bridge suitability criteria

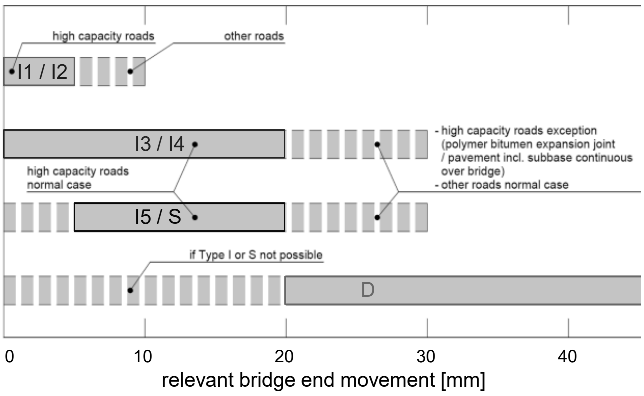
Movements of (semi-)integral bridge ends

The ASTRA guideline 12004 (2010) specifies a maximum bridge end movement of 20 mm on high capacity roads, and 30 mm on all other roads, for integral or semi-integral bridge ends.

The relevant movement $\Delta_h \leq 20 \ldots 30$ mm is the larger of the following values (SIA 260):

- magnitude of unidirectional movement of bridge end after installation of pavement and subbase, for occasional load cases ("seltene Lastfälle") due to:
  … girder contraction caused by temperature, shrinkage, prestressing and creep
  … horizontal movements caused by applied loads
- amplitude of cyclic movements of bridge end for frequent load cases caused by
  … girder expansion and contraction due to temperature variation ΔT
  … horizontal movements caused by applied loads

Bridge end movements as criterion for suitability of integral or semi-integral bridge end types (ASTRA RL 12004)



Bridge end types (ASTRA 12004), see behind for details:

I1 / I2:	integral, flexible without transition slab
I3 / I4:	Integral, flexible with transition slab
I5 / S:	integral, stiff (strongly curved bridges) or semi-integral
D:	jointed

EN 1990 and SIA 260 (English version) use different terms for the combinations of actions in the case of occasional / characteristic combinations:

EN 1990	*SIA 260*
characteristic combination	occasional load case (= "seltener Lastfall")
factor for combination value ψ_0	factor for occasional value ψ_0

For frequent (ψ_1) and quasi-permanent (ψ_2) combinations or load cases, the same expressions are used, also for the factors.

Note that in contrast to the design of expansion joints according to ASTRA 12004, the temperature variations are neither increased by a factor of 1.5 according to SIA 261, nor multiplied by an additional load factor of 1.5.

Support and articulation – (Semi-)integral bridge suitability criteria

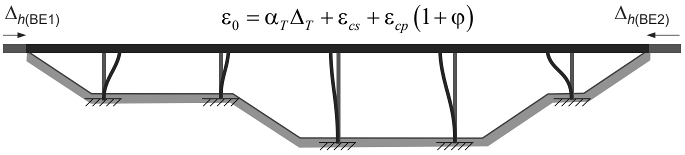
Movements of (semi-)integral bridge ends

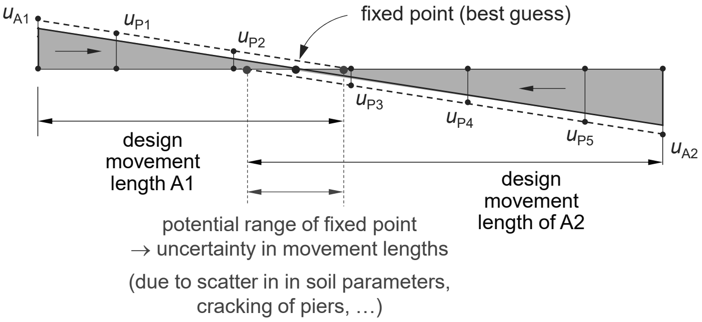
In conceptual design, a simplified approach can be used if

- the bridge is straight or slightly curved
- the fixed point is reliably known
- no significant horizontal movements of the bridge ends are caused by vertical or horizontal loads

→ the movements Δ_h of bridge ends are approximately proportional to
… the movement length and
… the free (unrestrained) girder deformations

Movements due to girder contraction
(schematic, bridge longitudinally stabilised by piers)





Support and articulation – (Semi-)integral bridge suitability criteria

Movements of (semi-)integral bridge ends

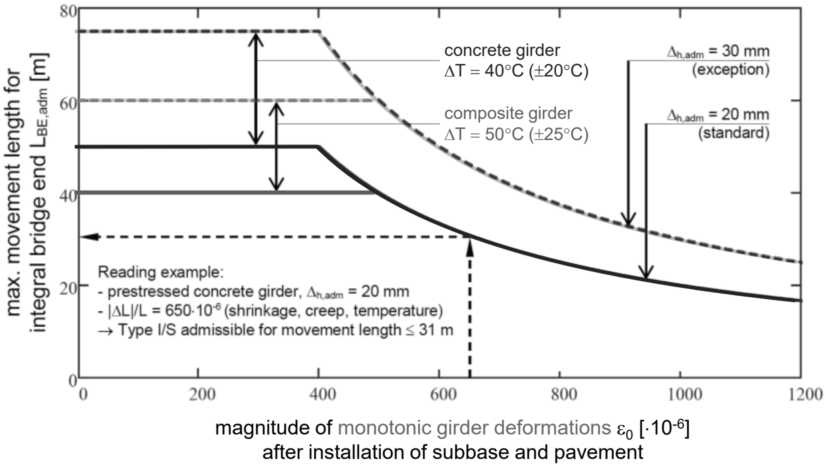
If the simplified approach is applicable, the chart on the right can be used to determine the maximum movement length for an integral bridge end:

- hyperbolic branches: monotonic contraction governs
- constant branches: cyclic movements govern

In the optimum case of a symmetrical layout (equal movement length of both bridge ends):

→ max. length of integral composite bridge:
80 m (high capacity roads)
120 m (other roads)

→ max. length of integral concrete bridge
(if creep and shrinkage have decayed):
100 m (high capacity roads)
150 m (other roads)



Reading example:
- prestressed concrete girder, $\Delta_{h,adm}$ = 20 mm
- $|\Delta L|/L = 650 \cdot 10^{-6}$ (shrinkage, creep, temperature)

→ Type I/S admissible for movement length ≤ 31 m

Illustrations: ASTRA Richtlinie 12004

Support and articulation

Integral and semi-integral bridges – Curved integral bridges

Support and articulation – Curved integral bridges

Movements of (semi-)integral bridge ends

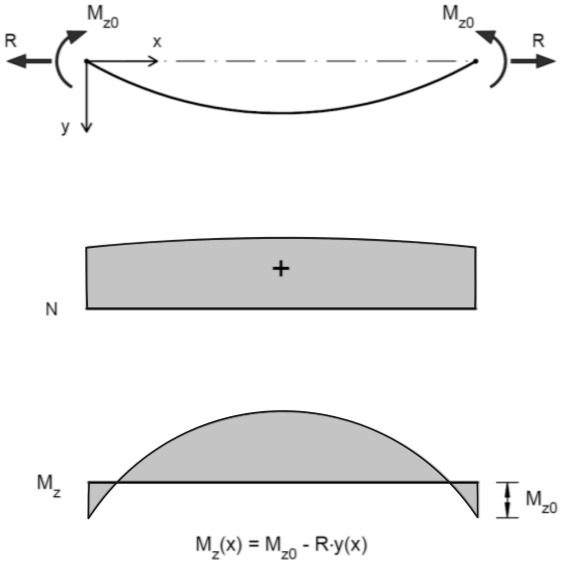
The behaviour of curved integral bridges is governed by

- the geometry and the stiffness conditions, including
  … aperture angle in plan
  … transverse and axial stiffness of girder
  … horizontal stiffness of piers and abutments
  … foundation stiffness

Due to the curvature, the restrained deformations of the girder cause not only

- axial restraint forces *N* (as in straight and slightly curved bridges), but also
- bending moments M_z (around z-axis = “in plan”)

→ transverse (radial) deformations of the girder
→ change of aperture angle and radius of curvature
→ girder virtually evades the axial restraint
→ significant reduction of axial restraint forces compared to straight bridges (under favourable stiffness conditions)



Support and articulation – Curved integral bridges

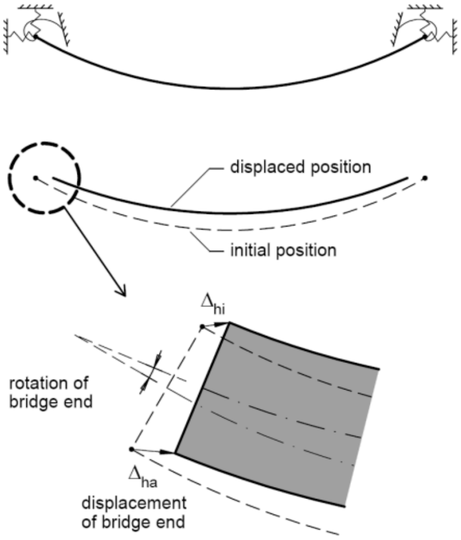
Movements of (semi-)integral bridge ends

The ends of curved integral bridges undergo not only

- longitudinal movements (as bridge ends of straight and slightly curved bridges), but also
- transverse movements and rotations around the vertical axis

→ maximum horizontal movement of bridge end at edge of bridge, rather than in the bridge axis

→ criterion for maximum bridge end movements (20…30 mm) has to be applied to the maximum resulting movement

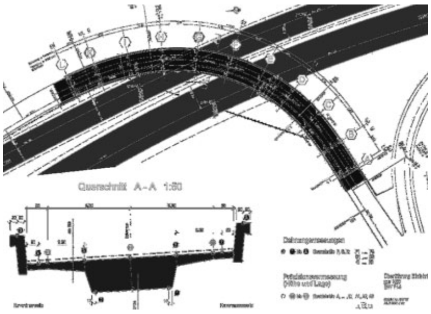


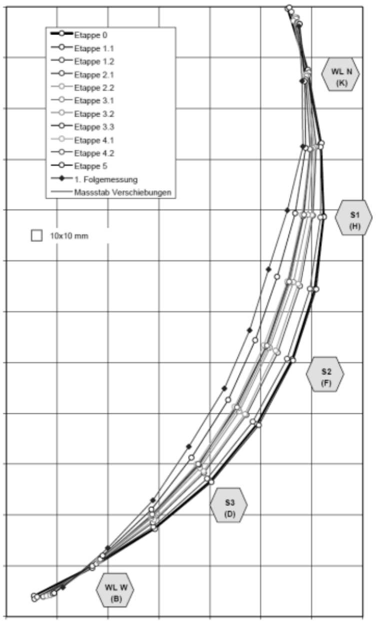
Support and articulation – Curved integral bridges

Movements of (semi-)integral bridge ends

This slide shows the results of on-site measurements on a curved integral bridge (Einfahrtsrampe BW714, Dreieck Zürich West, length 120 m), over a period of several months after construction.

It can clearly be seen that the bridge moves primarily in the radial direction, while the bridge ends rotate, but hardly move in plan.





Photos and illustrations: Kaufmann, W. “Integrale Brücken – Sachstandsbericht”, AGB Report No. 629, 2008 (Einfahrtsrampe BW714, Dreieck Zürich West, length 120 m, dsp Ingenieure + Planer AG, 2004)

Support and articulation

Integral and semi-integral bridges – Bridge end examples

Support and articulation – (Semi-)integral bridge end examples

Examples of (semi-)integral bridge ends

This slide, and the following, show examples of (semi-) integral bridge ends according to ASTRA guideline 12004

Flexible integral bridge end types (straight bridges):

- Type I1: No transition slab

→ short bridges ($\Delta_h \leq 5 \ldots 10$ mm) with low abutments; requires checking settlements of backfill

- Type I2: No transition slab, subbase cont. over bridge

→ short bridges ($\Delta_h \leq 5 \ldots 10$ mm) with low abutments; requires checking settlements of backfill

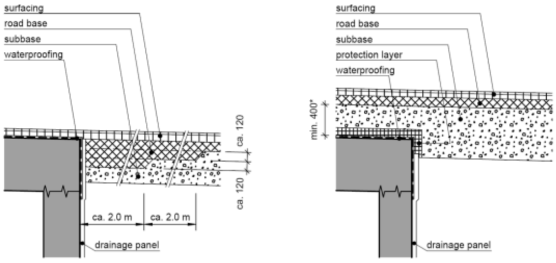
- Type I3: With transition slab

→ medium length bridges ($\Delta_h \leq 20 \ldots 30$ mm), standard case

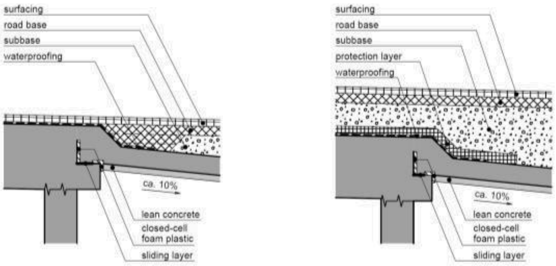
- Type I4: With transition slab, subbase cont. over bridge

→ medium-long bridges ($\Delta_h \leq 20 \ldots 30$ mm) with short spans

I1 / I2: Integral, flexible without transition slab



I3 / I4: Integral, flexible with transition slab



Illustrations: ASTRA Richtlinie 12004

Support and articulation – (Semi-)integral bridge end examples

Examples of (semi-)integral bridge ends

This slide, and the following, show examples of (semi-) integral bridge ends according to ASTRA guideline 12004

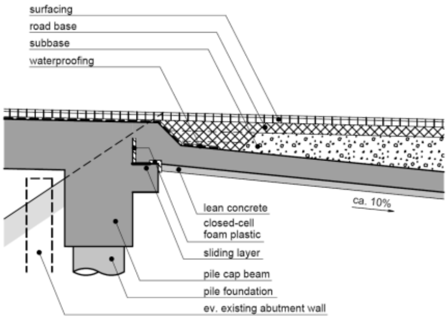
Flexible integral bridge end types (straight bridges):

Type I3: With transition slab

→ medium length bridges ($\Delta_h \leq 20 \ldots 30$ mm), standard case

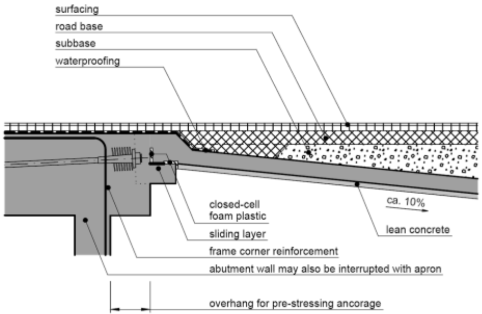
I3: Integral, flexible with transition slab

alternative solution with pile foundation



I3: Integral, flexible with transition slab

alternative solution with prestressing anchorage



Illustrations: ASTRA Richtlinie 12004

Support and articulation – (Semi-)integral bridge end examples

Examples of (semi-)integral bridge ends

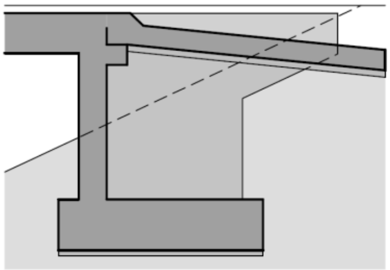
This slide, and the following, show examples of (semi-) integral bridge ends according to ASTRA guideline 12004

Stiff integral bridge end types (curved bridges):

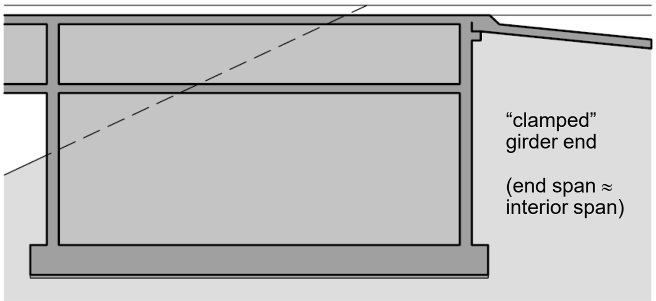
- Type I5

→ long strongly curved bridges ($\Delta_h \leq 20 \dots 30$ mm) with stiff bridge ends (reduce rotation of bridge ends in plan)

I5: integral, stiff (strongly curved bridges)



frame type



“clamped” girder end

(end span ≈ interior span)

Illustrations: ASTRA Richtlinie 12004

Support and articulation – (Semi-)integral bridge end examples

Examples of (semi-)integral bridge ends

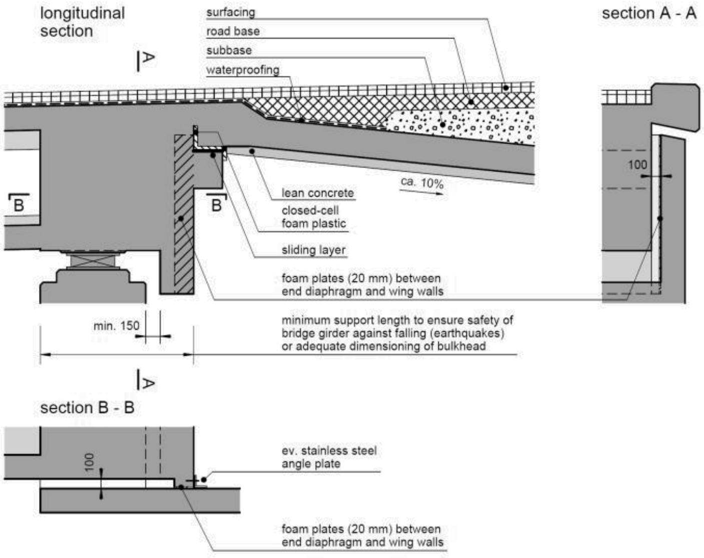
This slide, and the following, show examples of (semi-) integral bridge ends according to ASTRA guideline 12004

Semi-integral bridge end type:

- Type S: Semi-integral

→ long straight bridges ($\Delta_h \leq$ 20…30 mm)
… in cases with stiff abutments (low, on rock)
… modification of existing jointed bridge ends

S: semi-integral



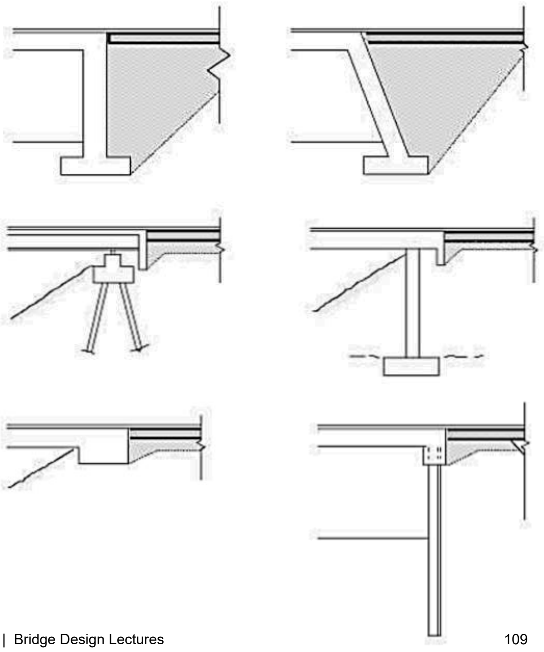
Illustrations: ASTRA Richtlinie 12004

Support and articulation – (Semi-)integral bridge end examples

Examples of (semi-)integral bridge ends

The provisions and designs for bridge ends differ significantly between clients / countries / designers.

The figure illustrates provisions for integral road bridge ends in the United Kingdom. In the UK, bridges up to a length of 60 m must be built with integral abutments, unless it is proven that this is not possible.



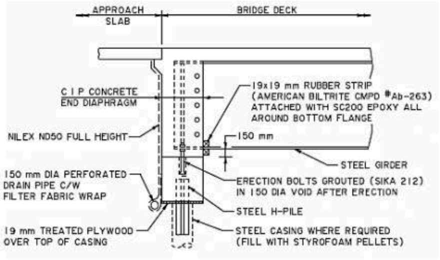
Illustrations: Design Manual for Roads and Bridges, Part 12, BD 42/96 Amendment No. 1, “The Design of Integral Bridges“, UK Highways Agency, 2003

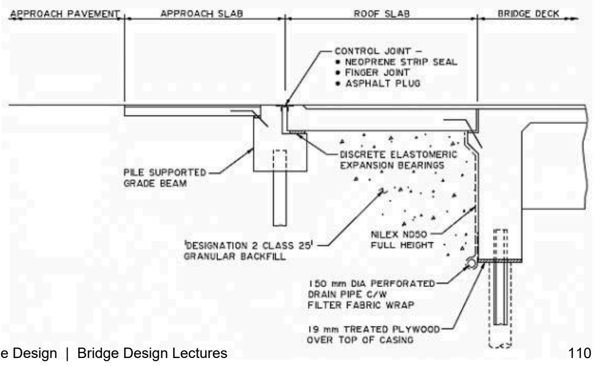
Support and articulation – (Semi-)integral bridge end examples

Examples of (semi-)integral bridge ends

The provisions and designs for bridge ends differ significantly between clients / countries / designers.

The figure illustrates provisions for integral road bridge ends in Canada (Alberta). The solution shown at the bottom is used to avoid pavement damages in long bridges (bridge length > 75 m for steel girders, > 100 m for concrete girders).





Illustrations: Bridge Structure Design Criteria, Appendix C, „Guidelines for Design of Integral Abutments“, Alberta Transportation Service, 2003