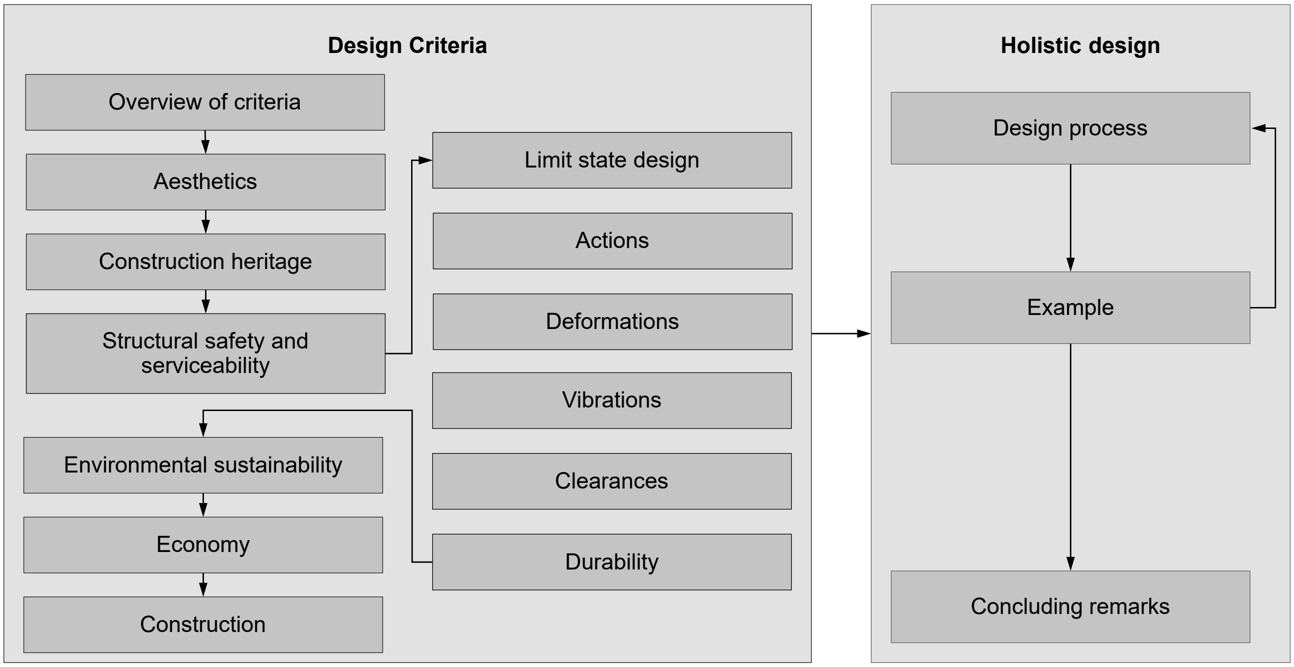
Conceptual Design
Entwurf und Bemessung



Design Criteria

Overview of criteria

Aesthetics

Construction heritage

Structural safety and serviceability

- Limit state design
- Actions
- Deformations
- Vibrations
- Clearances
- Durability

Environmental sustainability

Economy

Construction

Holistic design

Design process

Example

Concluding remarks

Conceptual Design

Design Criteria – Overview
Entwurfskriterien – Übersicht

Design Criteria – Overview

- Designing a bridge means developing its Structural Concept (Tragwerkskonzept), based on the given boundary conditions

- According to SIA 260, the Structural Concept defines
  - → the chosen structural system
  - → the most important
    - … dimensions
    - … construction material properties
    - … constructional details
  - → the envisaged methods of construction

The choice of the structural system must not be seen as a task limited to purely technical aspects (neither in bridges nor in buildings).

In the following, the bridge-specific aspects of structural design are dealt with.

Structural concept

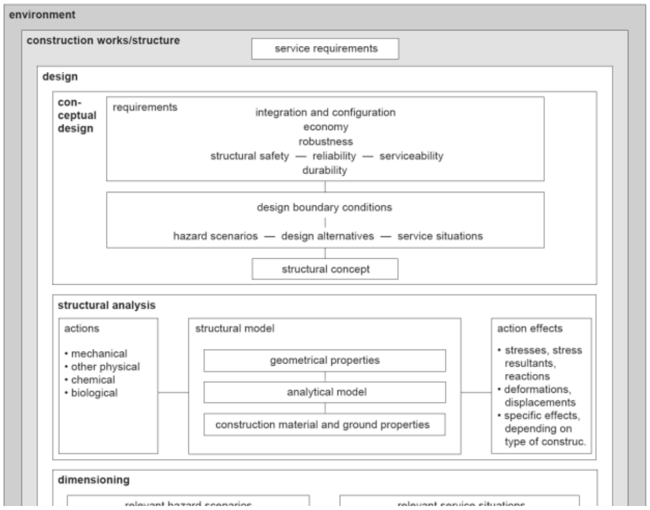
(Tragwerks-konzept)

Notes:

The Swiss Code SIA 260 Basis of Structural Design contains a concise description of the entire structural design process (terminology, conceptual design, structural analysis, dimensioning) and is highly recommended as reference.

Design Criteria – Overview

- Recommended reference: SIA 260 *Basis of Structural Design*



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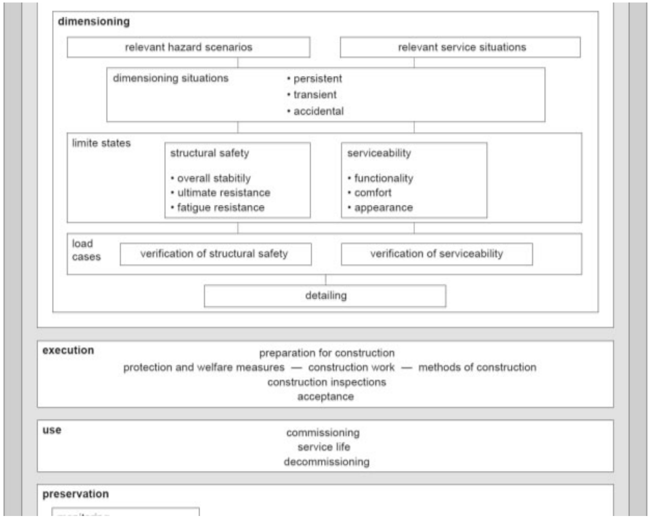

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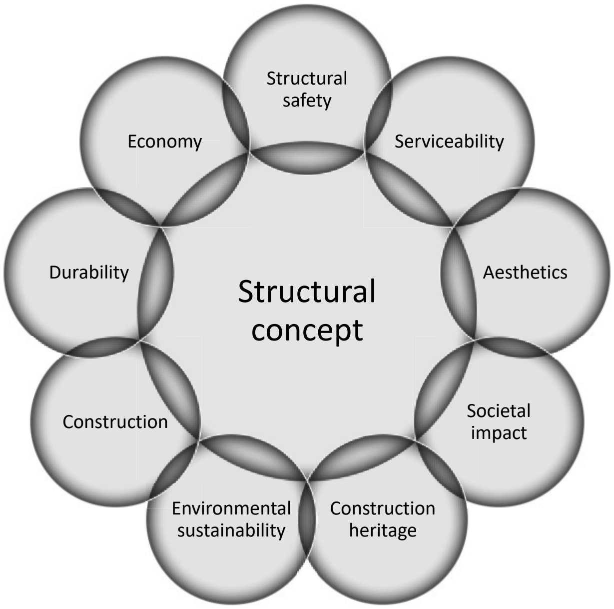
Notes:

The Swiss Code SIA 260 Basis of Structural Design contains a pertinent and concise description of the entire structural design process (terminology, conceptual design, structural analysis, dimensioning). This applies equally to bridges, and is highly recommended as reference.

The figure shows parts of Figure 1 in the cited reference, giving a schematic overview.

Design Criteria – Overview

- Designing a bridge means developing its Structural Concept, based on the given boundary conditions
- Designing a bridge is a multi-faceted task, where many different topics are to be mastered by structural engineers



Notes:

Structural safety includes other disciplines than structural engineering, such as geotechnical engineering (foundations), hydraulic engineering (scour), etc.

Serviceability includes all requirements related to the use of the bridge, including (but not limited to):
- geometry (horizontal and vertical alignment, number of lanes and usage, e.g. roadway, railway, pedestrian, bicycles)
- appearance (not in the sense of aesthetics, but functionality, e.g. deflections)
- drainage
- right-of-way

Design Criteria – Overview

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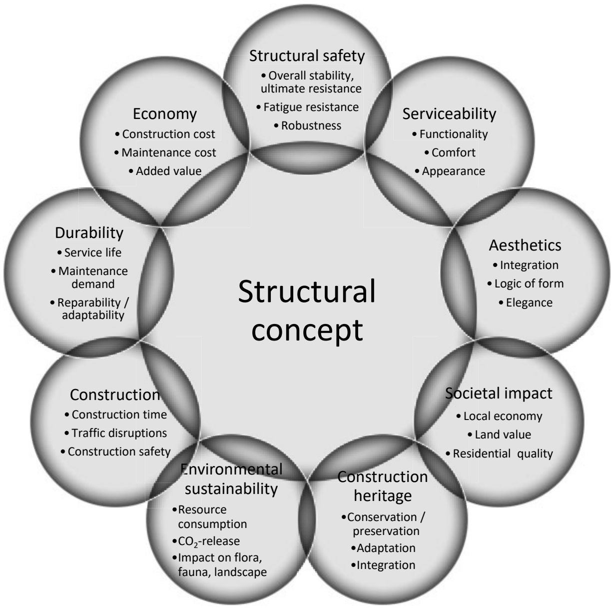


Structural concept

Structural safety
- Overall stability, ultimate resistance
- Fatigue resistance
- Robustness

Serviceability
- Functionality
- Comfort
- Appearance

Aesthetics
- Integration
- Logic of form
- Elegance

Societal impact
- Local economy
- Land value
- Residential quality

Construction heritage
- Conservation / preservation
- Adaptation
- Integration

Environmental sustainability
- Resource consumption
- CO_2-release
- Impact on flora, fauna, landscape

Construction
- Construction time
- Traffic disruptions
- Construction safety

Durability
- Service life
- Maintenance demand
- Reparability / adaptability

Economy
- Construction cost
- Maintenance cost
- Added value

Notes:

Some considerations on behalf of the bridge designer could include the following:

- When the bridged obstacle is a natural waterway, the bridge should ideally be placed where the (river)bed is relatively well defined, i.e. featuring a constant width and stable slopes.
- The bridge should be placed on a tangent whenever possible, i.e. not on a curved alignment.
- The bridge span and height should be minimised (within the site constraints).
- The axis of the bridge should be kept as perpendicular as possible to the axis of the obstacle, i.e. minimise angle of skew.
- The bridge should be founded on the most suitable/competent ground.
- The bridge should be adapted to its surroundings and minimise its impact on the environment.

Many of these will be treated in the course of the lecture.

Design Criteria – Overview

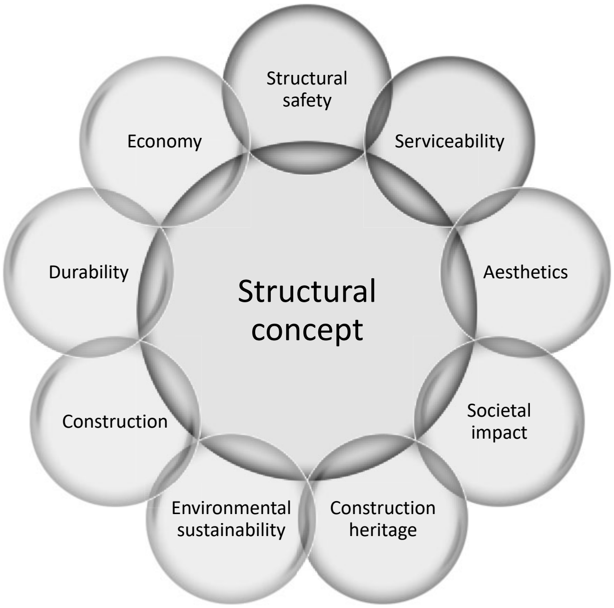
- Designing a bridge means developing its Structural Concept, based on the given boundary conditions.

- Designing a bridge is a multi-faceted task, where many different topics are to be mastered by structural engineers, as illustrated schematically in the figure by colour:

… "classical" structural engineering topics
… topics closely related to structural engineering
… topics beyond classic education of structural engineers

- Bridge designers therefore need to have broad interests, and at least a sufficient knowledge in all relevant fields to be able to communicate with experts.

(these design criteria are discussed in the following, except for societal impact which is left out due to limited time).



Design Criteria – Overview

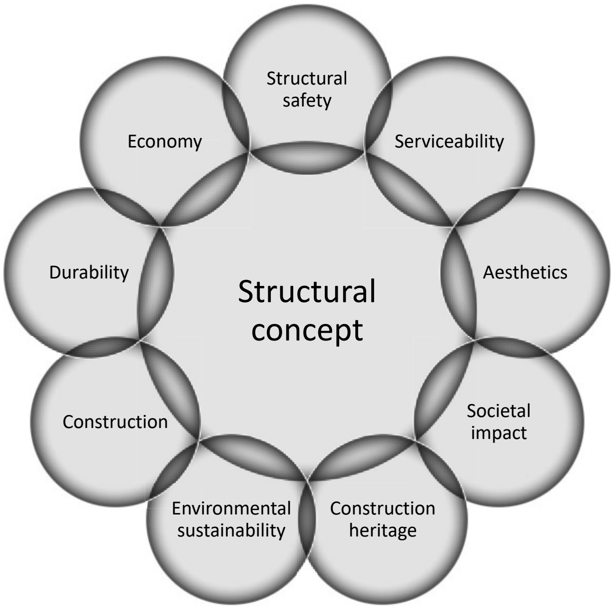
- Designing a bridge means developing its Structural Concept, based on the given boundary conditions

- Designing a bridge is a multi-faceted task, where many different topics are to be mastered by structural engineers

  … "classical" structural engineering topics
  … topics closely related to structural engineering
  … topics beyond classic education of structural engineers

- These criteria are not independent, and many of them are conflicting, or even contradictory

→ Rather than maximising individual criteria, an overall optimum solution is sought



Notes:

Example for interdependency: Durability affects most other criteria (serviceability, structural safety, economy, Environmental sustainability, societal impact, …)

Example for conflict: Stainless steel (reinforcement or structural steel) would be much more durable than conventional steel. However, it is much more expensive than conventional steel. Hence, hardly any bridge is built with stainless steel (or stainless steel einforcement) despite the consideration of life-cycle cost.

Design Criteria – Overview

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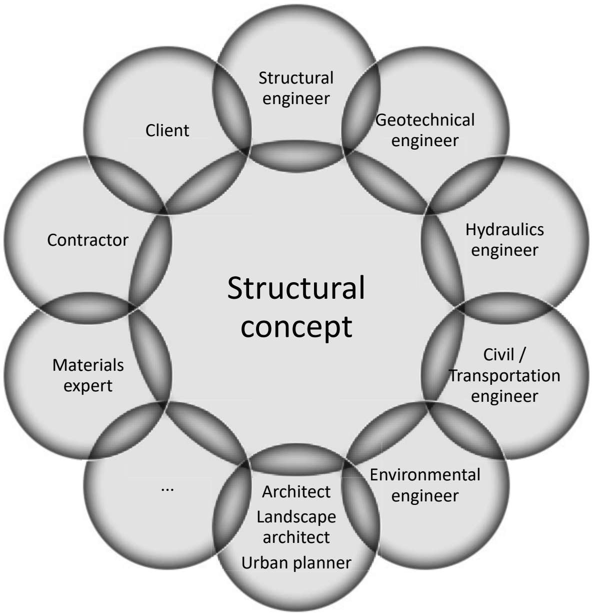
- These criteria are not independent, and many of them are conflicting, or even contradictory

→ Rather than maximising individual criteria, an overall optimum solution is sought

→ Most bridges are designed today in interdisciplinary design teams, covering the expertise relevant for a specific project, led by a structural engineer competent in all relevant topics (but supported by experts where required)



Notes:

Other specialties include Surveyors, Mechanical/Electrical Engineers (utilities, lighting, equipment for movable bridges, …), etc.

While large engineering firms cover many of these disciplines in-house, smaller companies often need to team up with specialists in the fields relevant for a specific project.

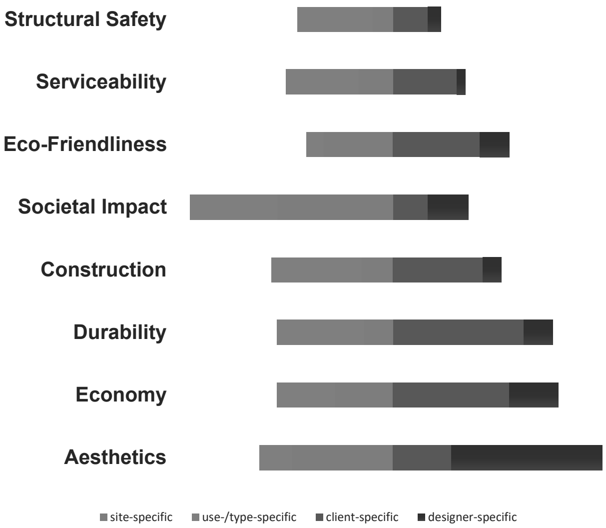
Design Criteria – Overview

- The design criteria depend to some degree on the specific project, in particular

  … the type and use of the bridge
  … the location of the bridge
  … the client's preferences
  … the designer's preferences

- If the bridge site and use are given, and the client is known, there remains much less variation in the design criteria

Note: The graphs to the right on this slide and the following are merely schematic



Notes:

While the design criteria for structural safety and serviceability of standard bridges are comprehensively covered by design codes and guidelines, non-standard bridge types, such as long-span cable supported structures or movable bridges, usually require the development of project-specific design criteria. Hence, there is more variation in the corresponding criteria in such cases.

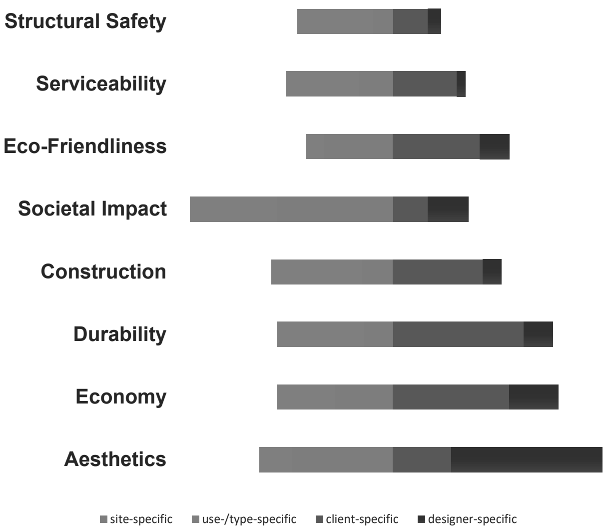
Design Criteria – Overview

- Most design criteria are project-specific, depending on
  … the type and use of the bridge
  … the location of the bridge
  … the client's preferences
  … the designer's preferences

- The project-specific design criteria should be agreed upon by the owner/client and the design engineers:
  → general aims for the use of the bridge
  → ambient conditions and third-party requirements
  → operational and maintenance requirements
  → special requirements of the owner
  → objectives of protection and special risks

  In Switzerland, these criteria are documented in the Service Criteria Agreement (Nutzungsvereinbarung), which is signed by owner and designer

Note: The graphs to the right on this slide and the following are merely schematic



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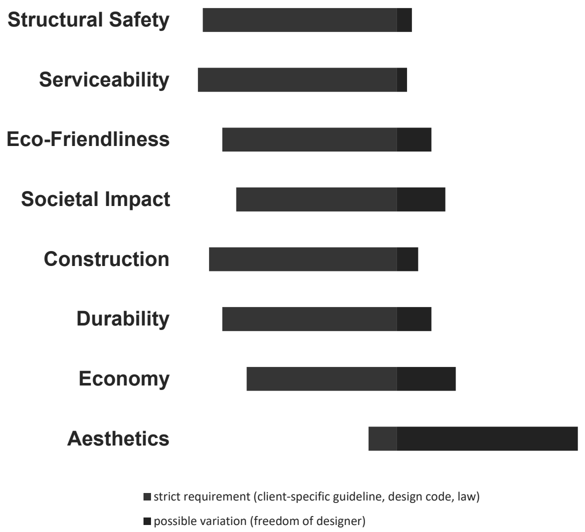
Design Criteria – Overview

- Many design criteria are based on strict requirements, such as guidelines imposed by the client, design codes, or even legal constraints

- Some design criteria are less restrictive and subjective, leaving room for the designer's creativity

- Many design criteria are subjective, and neither an overall design goal nor the relative importance of the individual criteria to achieve this goal can usually be objectively quantified
  - → No single "optimum" solution exists
  - → Finding a good solution is demanding
  - → Formalised decision making methods (weighted scoring method / "Nutzwertanalysen") are of limited use here, and may even be completely misleading



Notes:

Experience shows that weighted scoring and similar methods are often misused by adjusting the weights of the individual criteria until the intuitively or presumably "correct" result is achieved.

Conceptual Design

Design Criteria – Aesthetics
Entwurfskriterien – Gestaltung

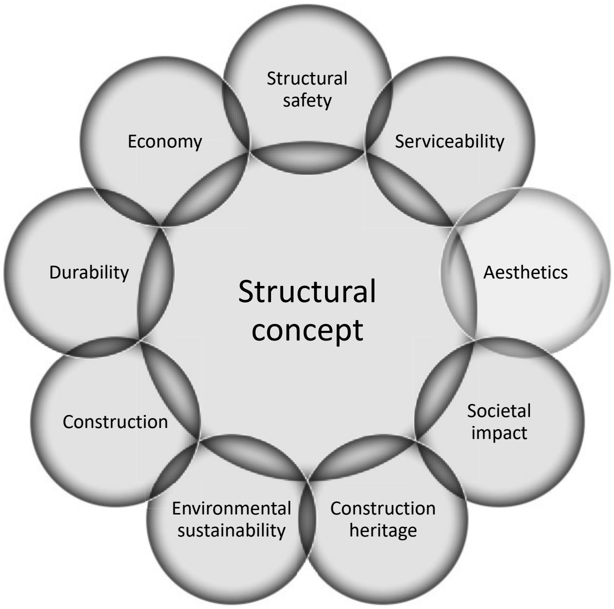
Design Criteria – Aesthetics

- Among all Design criteria, aesthetic quality is the most difficult one to measure
- Aesthetic quality is inherently subjective (individual perception, biased by the observer's socio-cultural background, education and personal preferences / taste)
- Aesthetic quality is hardly ever achieved by embellishment or ornamentation of an otherwise unsatisfactory design

→ Designing bridges of high aesthetic quality can hardly be taught in lectures

→ The course can merely
… insist on the high relevance of aesthetic quality and
… emphasise the responsibility of structural engineers for the built environment
… foster the awareness for aesthetics (open the eyes)

→ Aesthetics will be treated as "embedded topic" throughout the lecture (here, only some basic aspects are discussed)



Design Criteria – Aesthetics

- Bridges are prominent elements of public infrastructure
- Bridges are designed for a long lifespan (centuries)
- Bridges have a high impact on the quality of the built environment
- Bridges are perceived by many people, whether the designer cares about aesthetic quality or not

→ The aesthetic quality of bridges is highly relevant

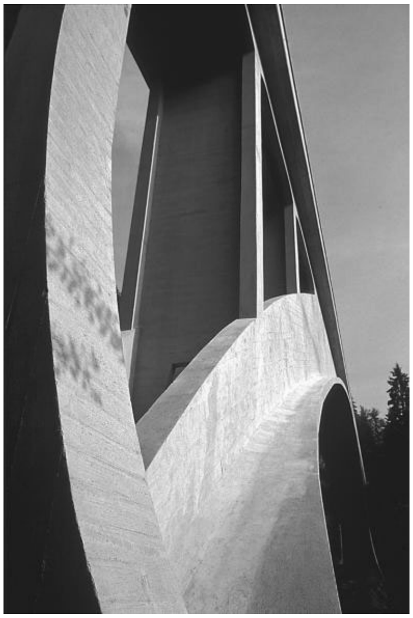


Photo: Salginatobel Bridge, R. Maillart, from P. Marti, Ingenieur-Betonbau

Design Criteria – Aesthetics

- Bridge designers are responsible for the aesthetic quality of their bridges, as much as for structural safety and serviceability
- Bridges often have the potential to greatly increase the quality of exterior spaces if the opportunities are seized

  → Responsible bridge designers care about the quality of the built environment

Photo: Sunnibergbrücke, Ch. Menn, from P. Marti, Ingenieur-Betonbau (Photo © O. Monsch)

Design Criteria – Aesthetics

Even though aesthetic quality is inherently subjective, there are some generally accepted principles to achieve an aesthetically satisfactory design:

- *Eduardo Torroja* postulated the “logic of form” (“Razón y ser de los tipos estructurales”), which is closely related to L. Sullivan’s maxim *form follows function* dating back to 1896
- *David Billington* suggested that an efficient bridge is not only economical, but also elegant: His axiom was “efficiency – economy – elegance”
- *Juan José Arenas* insisted in the importance of ethics, rather than economy (which is related, see next slide)
- *Fritz Leonhardt* established an entire set of aesthetic design principles
- Many authors postulated similar principles (e.g. *A.C. Liebenberg*, *Ch. Menn*, *M. Virlogeux*, …), whose common denominator can be summarised as:
  - → Integration (in landscape, urban context, …)
  - → Logic of form
  - → Elegance (form, proportion, order, …)

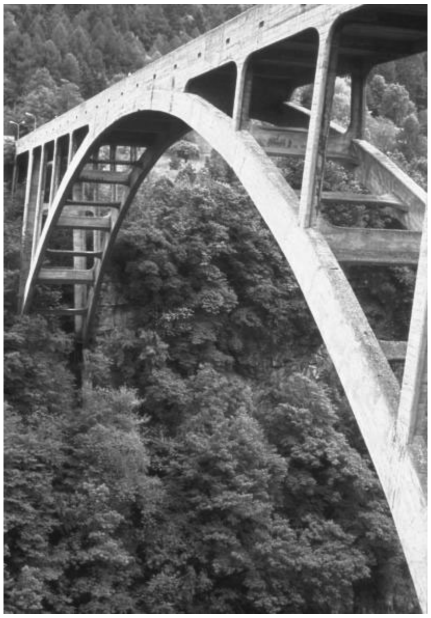
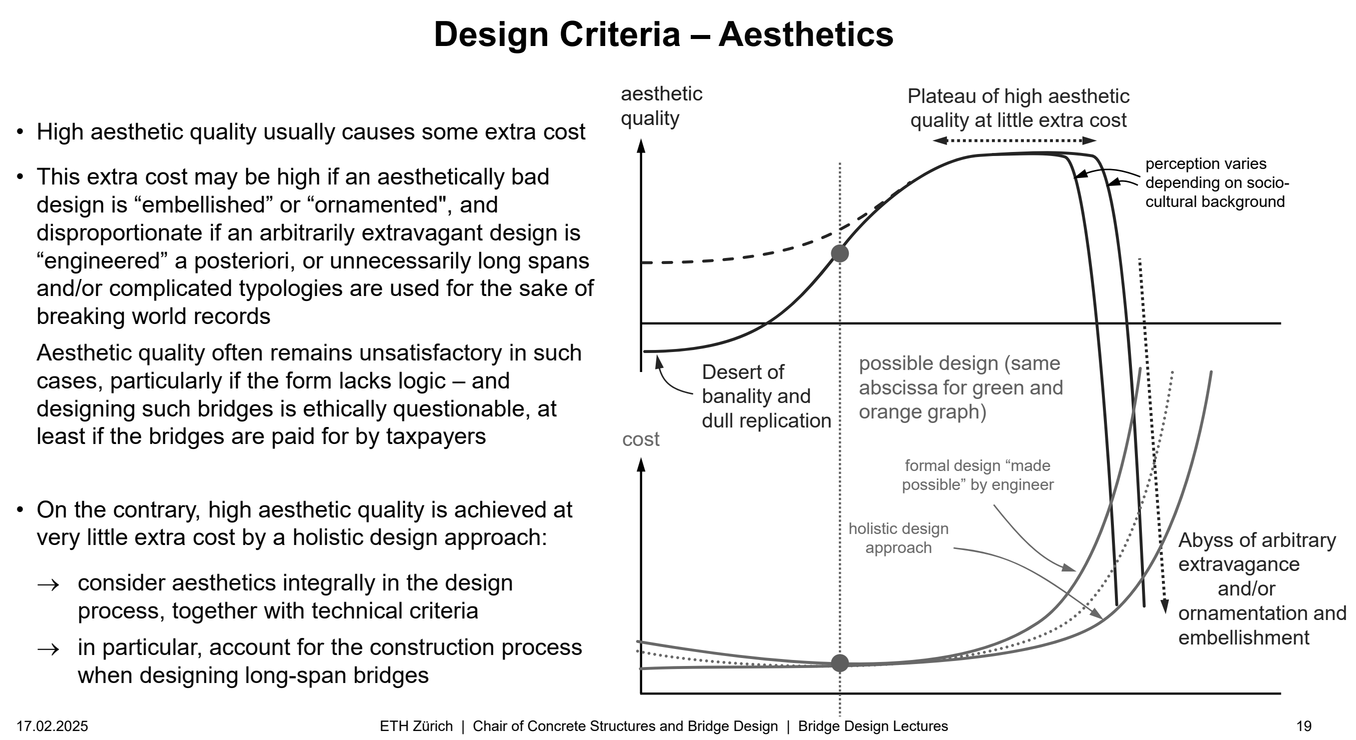


Photo: Pont du Gueroz, A. Sarrasin, 1934, from P. Marti, Ingenieur-Betonbau



Design Criteria – Aesthetics

- High aesthetic quality usually causes some extra cost
- This extra cost may be high if an aesthetically bad design is “embellished” or “ornamented", and disproportionate if an arbitrarily extravagant design is “engineered” a posteriori, or unnecessarily long spans and/or complicated typologies are used for the sake of breaking world records

  Aesthetic quality often remains unsatisfactory in such cases, particularly if the form lacks logic – and designing such bridges is ethically questionable, at least if the bridges are paid for by taxpayers

- On the contrary, high aesthetic quality is achieved at very little extra cost by a holistic design approach:
  - → consider aesthetics integrally in the design process, together with technical criteria
  - → in particular, account for the construction process when designing long-span bridges

Billington postulated that efficient structures – virtually automatically – would also be elegant and economical. Indeed, many extraordinary bridges, such as Robert Maillart’s bridges used as prominent examples by Billington, were in fact the most economical proposals at the time.

However, except for very long spans, the cheapest bridge is rarely particularly efficient or elegant today. The low cost of building materials, along with the high cost of skilled labour, are among the main reasons for this unfortunate situation. While the author hopes that the urgent need to reduce material consumption and greenhouse gas emissions to mitigate climate change will favour the design of structurally efficient bridges in the near future, convincing bridge designs currently entail higher costs in many cases.

However, provided that (i) aesthetics considerations are an integral part of the design process, together with the technical criteria, and (ii) the design accounts for construction requirements, the extra costs required to achieve high aesthetic quality are moderate and may be justified in many cases by the resulting higher quality of the built environment.

Design Criteria – Aesthetics

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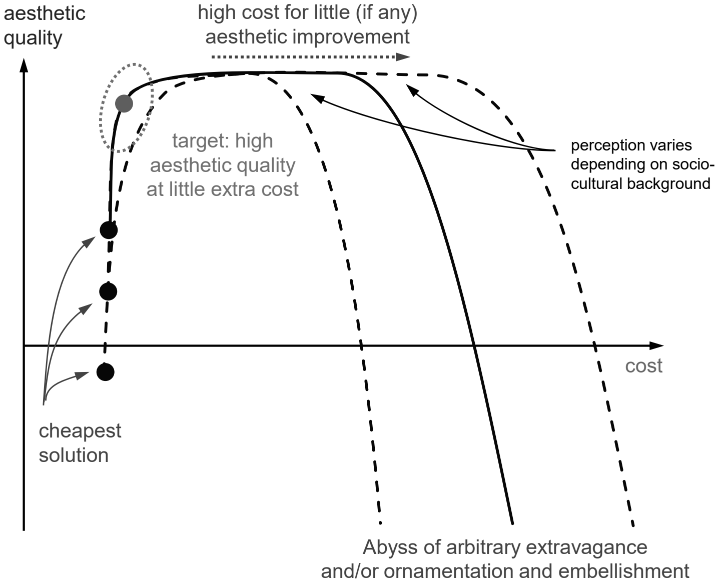
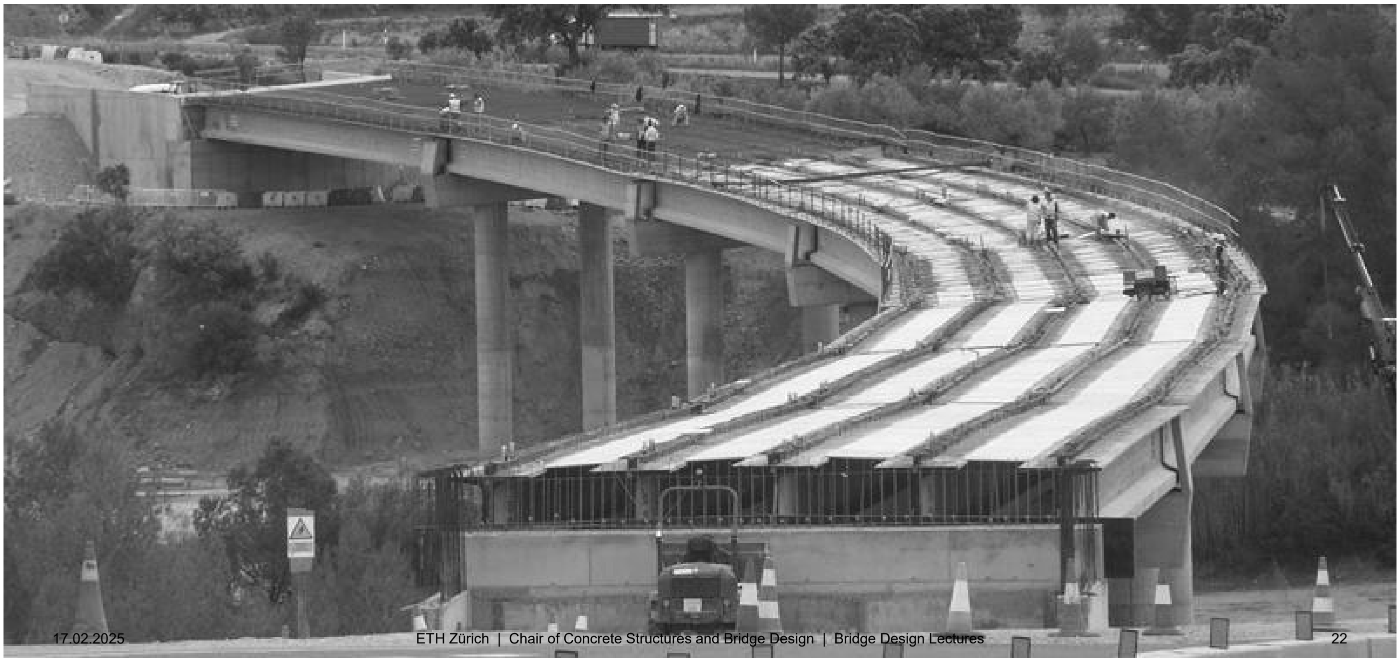


Design Criteria – Aesthetics

Desert of banality and dull replication?

Design Criteria – Aesthetics



Desert of banality and dull replication?

Design Criteria – Aesthetics

On the edge (?) of arbitrary extravagance – disproportional cost since construction process was no design criterion.

Photo: Sheikh Zayed Bridge, Zaha Hadid © Zaha Hadid Architects

Design Criteria – Aesthetics

On the edge (?) of arbitrary extravagance – disproportional cost since construction process was no design criterion.

Photo: Sheikh Zayed Bridge, Zaha Hadid © Zaha Hadid Architects

Design Criteria – Aesthetics

Abyss of arbitrary extravagance?

Photo: Puente del Milenio, Ourense, Pondio Ingenieros (photo W. Kaufmann)

Design Criteria – Aesthetics

Highest aesthetic quality at no extra cost: Maillart won most competitions because his bridge was the cheapest.

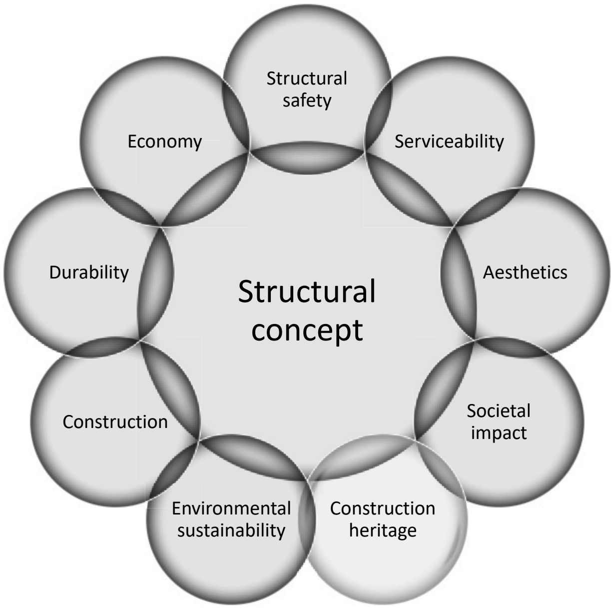
Photo: Salginatobel Bridge, R. Maillart, from P. Marti, Ingenieur-Betonbau

Conceptual Design

Design Criteria – Construction heritage
Entwurfskriterien – Konstruktionserbe / Denkmalpflege

Design Criteria – Construction heritage

- Another design criterion which is difficult to quantify is construction heritage. All bridges become part of it once built. However, only few will ever be worthy of protection.
- The design criterion construction heritage thus refers to situations where:
  - → an existing bridge worthy of protection needs to be replaced or adapted, e.g. due to a required widening
  - → a new bridge is built near a protected monument
- Typically, governmental commissions for monument preservation decide if a bridge is worthy of protection
  - → due to their visible value and character as monument
  - → as milestones of technological development (e.g. first prestressed bridges). This intangible construction heritage is not (yet) protected in CH
- Any interventions affecting protected bridges need to be coordinated with the responsible bodies.
- Even if a historic bridge is not protected, preserving it entirely or partly should be considered as an option in developing the structural concept.



Design Criteria – Construction heritage

- While interventions affecting construction heritage are highly site-specific and need to be coordinated with the responsible bodies, the following guidelines apply:
  - → preserve protected bridges e.g. by considering
    … alternative locations for a new bridge
    … alternative uses of the protected bridge (e.g. use as footbridge with reduced traffic loads)
  - → minimise interventions in protected bridges, preserving as much as possible of the original structure
  - → do not mimic historic construction when replacing or complementing a protected bridge (reconstructions may be viable in exceptional cases, see next slide)
  - → minimise impact of new structure on protected one (avoid spectacular designs, see next slide)
  - → develop a structural concept respecting and, if possible, reflecting the construction heritage (e.g. by adopting the span layout, see photo on this slide or referencing the protected structure – including intangible values – in modern design, see next slide)

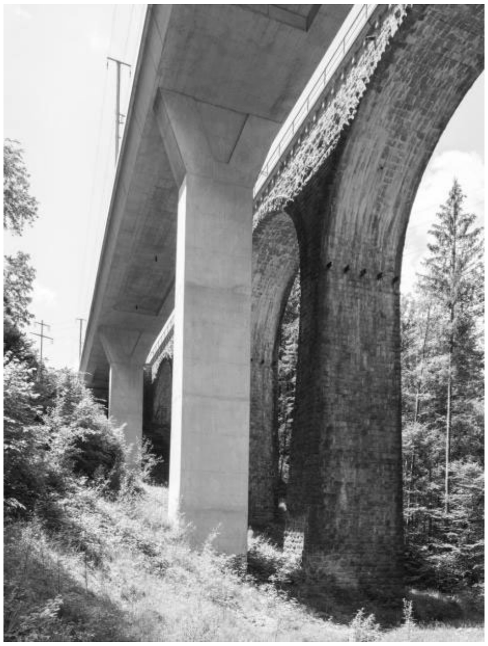
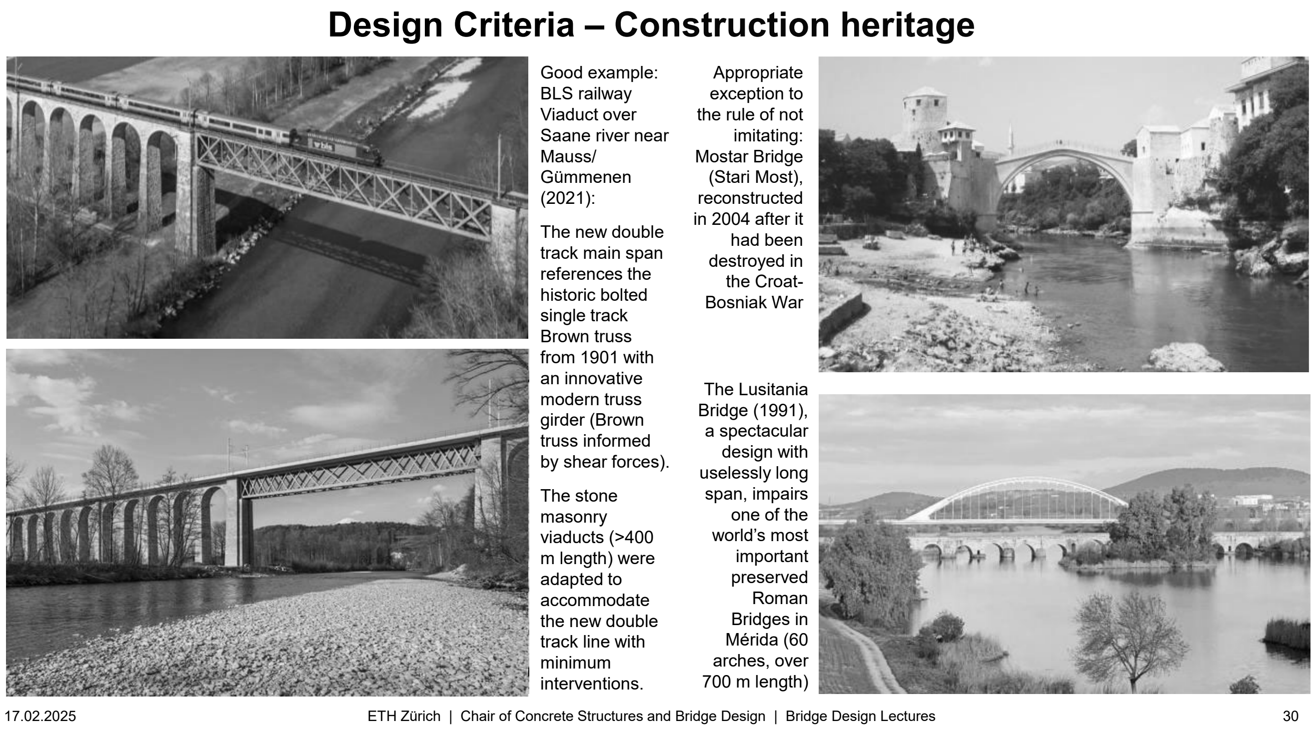


Photo: Kirchtobelviadukt SOB, © dsp Ingenieure + Planer AG



Design Criteria – Construction heritage

Good example: BLS railway Viaduct over Saane river near Mauss/ Gümmenen (2021):

The new double track main span references the historic bolted single track Brown truss from 1901 with an innovative modern truss girder (Brown truss informed by shear forces).

The stone masonry viaducts (>400 m length) were adapted to accommodate the new double track line with minimum interventions.

Appropriate exception to the rule of not imitating: Mostar Bridge (Stari Most), reconstructed in 2004 after it had been destroyed in the Croat-Bosniak War

The Lusitania Bridge (1991), a spectacular design with uselessly long span, impairs one of the world's most important preserved Roman Bridges in Mérida (60 arches, over 700 m length)

Quote by Javier Manterola (2014) on the Lusitania Bridge:

"El segundo puente es el puente de Lusitania, el puente de Calatrava, que más que un puente es un monumento y así lo ha entendido la ciudad que lo considera una pieza formidable dentro de la arquitectura de la ciudad. Recuerdo cuando se produjo el concurso que nos presentamos y nos quedamos asombrados de la propuesta de Calatrava y supimos enseguida que no seríamos los ganadores. La propuesta de Calatrava había seducido al tribunal y contra la seducción no existe más arma que una seducción mejor. Recuerdo que cuando argumentábamos que ese puente no era para ese río en ese sitio, con un vano principal que enfatizaba el puente y que podía estar sobre un cauce seco, lo que bien podía ocurrir y ha ocurrido. Cuando vimos que nuestros razonamientos no rompían la seducción, recomendamos al Sr. Alcalde que hiciese un azud aguas abajo para que el río tuviese siempre agua y se evitase el bochorno de ver un gran arco saltando sobre tierra. En el fondo nuestra recomendación fue que ya que no tenía un puente para un río, que fabricase un río para un puente."
[https://lascarreterasdeextremadura.blogspot.com/2014/06/los-puentes-de-merida-por-javier.html]

(The second bridge is the Lusitania Bridge, Calatrava's bridge, which is more than a bridge, it is a monument and that is how the city has understood it, considering it a wonderful piece of the city's architecture. I remember when the competition took place that we applied and were amazed by Calatrava's proposal and we knew straight away that we would not be the winners. Calatrava's proposal had seduced the jury and against seduction there is no other weapon than a better seduction. I remember when we argued that this bridge was not for that river in that place, with a main span that emphasised the bridge and that it could be over a dry riverbed, which could well happen and has happened. When we saw that our reasoning did not break the seduction, we recommended to the Mayor to build a dam downstream so that the river would always have water and avoid the shame of seeing a large arch jumping over land. Basically, our recommendation was that since there was no bridge for a river, he should build a river for a bridge").

Photos:

Left side: BLS Saaneviadukt Gümmenen (Fürst Laffranchi GmbH): top Wikipedia © Kabelleger / David Gubler, bottom wikimedia commons, © Idohl

Right side Mostar Bridge © Wikipedia Commons; Mérida Bridges kfm

Conceptual Design

Design Criteria – Structural Safety and Serviceability
Entwurfskriterien – Tragsicherheit und Gebrauchstauglichkeit

Design Criteria – Structural Safety and Serviceability

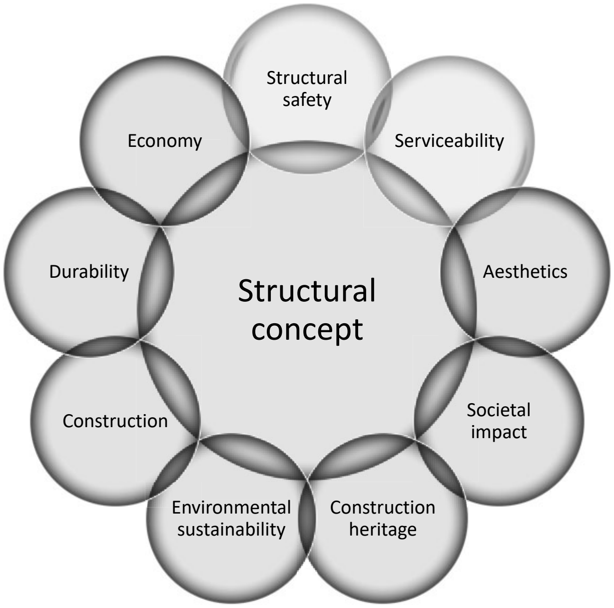
- Structural safety and serviceability have many points In common (loads, limit state design, etc.)
  → treated in same chapter of this the lecture

- The objectives of structural safety and serviceability are of paramount importance
  → specified in detail in design codes

- The project-specific service criteria should be agreed upon by the owner/client and the design engineers
  (→ Service Criteria Agreement / Nutzungsvereinbarung, see overview)

- The basic structural concept, i.e. the
  … structural system
  … relevant dimensions, material properties and details
  … methods of construction

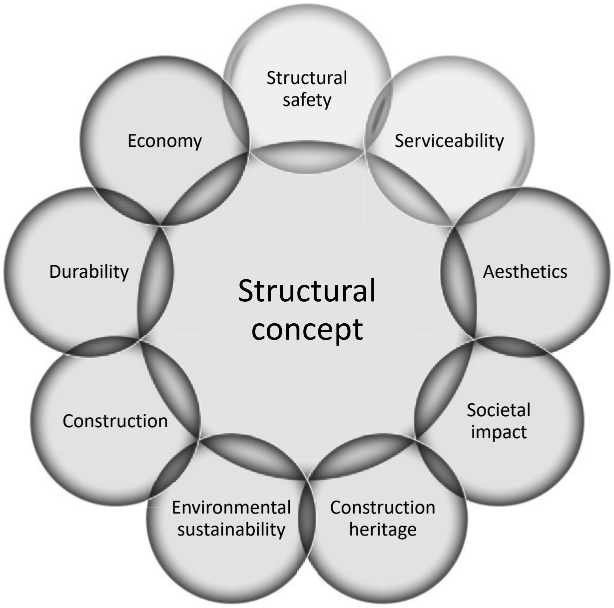
  is developed based on these service criteria



Design Criteria – Structural Safety and Serviceability

- Depending on the concept chosen, specific requirements for the detailed design (dimensioning), execution, use and preservation are obtained:
  - → hazard scenarios (Gefährdungsbilder) considered
  - → requirements of structural safety, serviceability and durability and measures needed to guarantee them
  - → ground conditions
  - → important assumptions in the structural models
  - → accepted risks
  - → other conditions relevant to the design

  In Switzerland, these requirements are documented in the Basis of Design (Projektbasis), which is usually updated during the detailed design



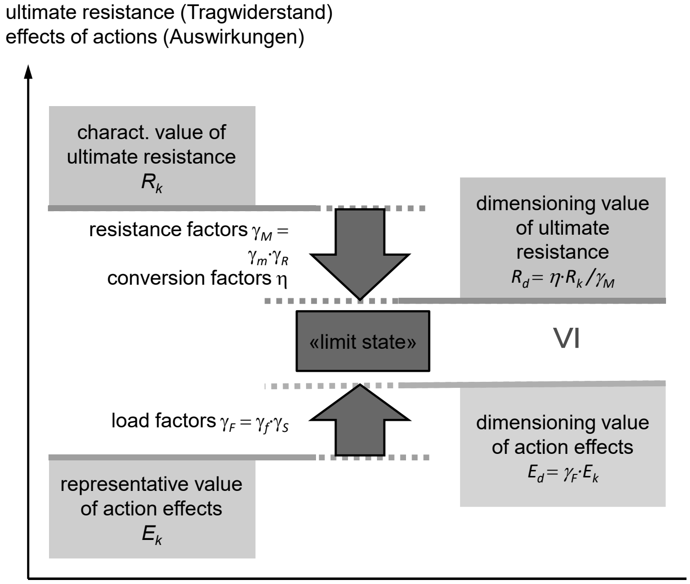
Conceptual Design

Design Criteria – Structural Safety and Serviceability
Limit State Design
Bemessung nach Grenzzuständen

Design Criteria – Structural Safety and Serviceability: Limit State Design

- Most modern design codes follow the Limit States approach, aka Load and Resistance Factor Design (LRFD)
- This approach is illustrated on the right for structural safety (often referred to as ultimate limits state = "ULS"), but also applicable to serviceability design (serviceability limit state = "SLS")
- Some codes still allow the use of Allowable Stress Design

- Students are assumed to be familiar with the concept of LRFD and its application to
  … the design of the basic construction materials (concrete, steel, timber)
  … and their interaction with soil (foundations, retaining structures)
- Thus, the lecture focuses on bridge-specific aspects of the design process



ultimate resistance (Tragwiderstand)
effects of actions (Auswirkungen)

charact. value of ultimate resistance R_k

resistance factors $\gamma_M = \gamma_m \cdot \gamma_R$
conversion factors η

dimensioning value of ultimate resistance $R_d = \eta \cdot R_k / \gamma_M$

«limit state»

VI

load factors $\gamma_F = \gamma_f \cdot \gamma_S$

dimensioning value of action effects $E_d = \gamma_F \cdot E_k$

representative value of action effects E_k

Notes:

"Failure of structures almost always results in injury and loss of life. Structural safety is therefore of primary importance right from the beginning of conceptual design and should not be influenced or affected by other objectives such as cost, aesthetic shaping etc." [Christian Menn, 2010]

"When analysing the causes of structural failures today, I find that there is hardly any case, which could have been prevented by more detailed calculation. The basic cause of most catastrophes was either that possibilities of failure were never even considered, conditions were not thoroughly investigated or that in some way rashness or even foolishness was predominant during design or construction. Also on some occasions, successful structures have been the cause of failure in later structures when seemingly unimportant changes, such as in size or slenderness, turned secondary factors into major influences. It is also doubtful whether the safety theory based on a probability approach, which is now the basis for all new standards internationally, is likely to reduce the incidence of failure and collapse of structures. This is because the causes are not statistically distributed, but are rather gross errors that do not fit into any probability calculation. Such concepts are perhaps better suited for appraising the serviceability of our structures." [Joachim Scheer, 2010]

Design Criteria – Structural Safety and Serviceability: Limit State Design

Bridge Design Codes/Standards used around the world include publications by:

Europe

- SIA (Swiss Society of Engineers and Architects)
- EN (European Standards)
- SETRA (service d'études techniques des routes et autoroutes)

North America

- AASHTO (American Association of State Highway and Transportation Officials)
- AREMA (American Railway Engineering and Maintenance-of-Way Association)
- CSA (Canadian Standards Association)

Asia

- China National Standards (GB)
- Japanese Association of Highways

sia

SN

SIA 260

Grundlagen der Projektierung von Tragwerken

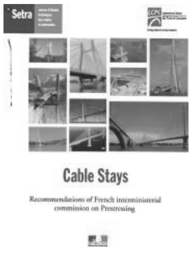
260

sia

SN

EN 1990:2002

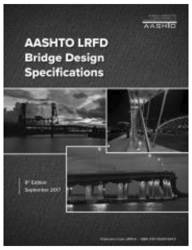
Eurocode: Grundlagen der Tragwerksplanung



Setra

Cable Stays

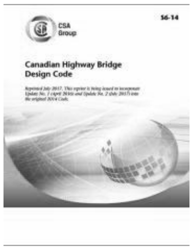
Recommendations of French interministerial commission on Prestressing



AASHTO

AASHTO LRFD Bridge Design Specifications

8th Edition
September 2017



CSA Group

S6-14

Canadian Highway Bridge Design Code

GB

中华人民共和国国家标准
NATIONAL STANDARD OF THE PEOPLE'S REPUBLIC OF CHINA

GB 50917-2013

Code for design of steel and concrete composite bridges
钢-混凝土组合桥梁设计规范

Issued by: The Standardization Administration of the People's Republic of China

Design Criteria – Structural Safety and Serviceability: Limit State Design

SIA 260 defines the following Limit States:

Ultimate Limit States “ULS”

- Concern safety of structure and persons
- Involve:
  - → Overall stability of structure
  - → Ultimate resistance of structure or one of its structural members (incl. supports & foundations)
  - → Fatigue resistance of structure or one of its structural members
- Consider:
  - → Permanent actions
  - → Variable actions
  - → Accidental actions

Always consider: construction phases, operation phase, future maintenance needs

Notes:

It should be noted that the objectives under the above limit states should be viewed as minimum requirements. The Engineer in collaboration with the Owner/Supervisory Authority may choose to follow more stringent requirements to better suit the function of the bridge. For example, for certain extreme events, e.g. a seismic event with a relatively low return period (say 500 years), it may be prudent to design the bridge to sustain minimal or no damage so that it can act as a lifeline during the post-earthquake operations.

Photo: Overpass collapse near Ancona, Italy, 2017

Design Criteria – Structural Safety and Serviceability: Limit State Design

SIA 260 defines the following Limit States:

Serviceability Limit States “SLS”

- Concern functionality & appearance of structure, user comfort
- Criteria applied to:
  - → Deformations (functionality, appearance, deterioration)
  - → Vibrations (functionality, comfort)
  - → Defective sealing (functionality, durability)
  - → Cracking/Connection slipping (appearance, durability)
  - → Effects on stream flow (environmental impacts)

Notes:

It should be noted that the objectives under the above limit states should be viewed as minimum requirements. The Engineer in collaboration with the Owner/Supervisory Authority may choose to follow more stringent requirements to better suit the function of the bridge. For example, for certain extreme events, e.g. a seismic event with a relatively low return period (say 500 years), it may be prudent to design the bridge to sustain minimal or no damage so that it can act as a lifeline during the post-earthquake operations.

Photo: Excessive deformations, Parrot’s Ferry Bridge, Stanislaus River, California, USA (lightweight concrete bridge built by free-cantilevering, with insufficient prestressing to compensate deflections
Photo credit http://www.bridgeofweek.com/2013/06/calaveras-county-california-bridges_6.html

Parrotts Ferry is a submerged reservoir bridge whose piers are usually hidden beneath New Melones Lake in Central California’s Calaveras County. At 640 feet (195 mtrs), the main span is one of the longest prestressed concrete beam bridges ever built in the United States. One of the earliest bridges to use a special lightweight concrete, the central span had sagged nearly a foot about 5 months after opening and nearly another foot in the ten years that followed. Concerned about the displacement, tests were done to the bridge and it was decided to add a large bracing span underneath the central third of the bridge to prevent any further sagging. The bridge has been performing perfectly ever since [http://www.highestbridges.com/wiki/index.php?title=Parrotts_Ferry_Bridge]

Conceptual Design

Design Criteria – Structural Safety and Serviceability

Actions

Einwirkungen

Design Criteria – Structural Safety and Serviceability: Actions

Depending on the project, the following types of actions have to be considered:

Permanent Actions

- Dead loads: self-weight of the structure (Eigenlast)
- Superimposed dead loads: self-weight of non-structural components (Auflast) (attachments, utilities)
- Creep and Shrinkage
- Prestress forces including secondary effects
- Locked-in forces resulting from the construction process

Actions imposed by the ground (permanent or transient)

- Earth pressures, downdrag forces
- Soil surcharge
- Water pressure
- Stream flow pressure (see notes)

Variable Actions

- Live Loads (Nutzlasten) – including:
  - Vertical vehicular live load (incl. dynamic allowance)
  - Horizontal vehicular live load (braking, centrifugal and nosing = Schlingerkraft)
  - Vertical and horizontal pedestrian live load
- Friction loads at sliding surfaces (e.g. bearings)
- Wind Loads – on structure and on live load
- Temperature effects – uniform and gradient
- Snow load (see notes)

Accidental (Extreme) loads

- Seismic (earthquake) loads
- Ship impact / Vehicular collision / Train derailment
- Avalanche load
- Ice load
- Blast loading

Notes:

- Future overlays and planned widenings should be considered in the dead load / superimposed dead load
- Some codes specify higher load factors for non-structural components than for the dead load. According to SIA 260, no distinction is made, but superimposed dead loads need to be neglected when favourable, if they are removable
- Snow load can usually be neglected, since it does not have to be superimposed with traffic loads
- Water pressure and stream flow pressure may also be treated as accidental loads (in case of extreme event water levels)
- Ship (vessel) impact causes very high loads, leading to significant cost increase in the substructure. In the case of large vessels (cargo ships), these forces cannot be resisted, and pier needs to be considered as hazard scenario. If possible, solutions without piers in the navigational channel should always be checked as an alternative.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads

- The following slides illustrate the traffic load models and provisions of SIA 261 (which is similar to EN1991-2, see notes). Other codes have similar provisions.
- The live loads are introduced following the categories of SIA 261, i.e.
  - non-motorised traffic (→ footbridges, sidewalks)
  - road traffic (→ road bridges)
  - rail traffic (→ railway bridges)
- Project-specific criteria may need to be developed for live loads not explicitly covered, such as:
  - special vehicles, military loads, tramway loads
  - bridges with combined road and rail traffic
  - bridges with spans longer than 200 m

Notes:

For illustration purposes reference is made to the traffic load models and provisions outlined in the SIA/Eurocode. Other codes have similar provisions.
Reference documents:

- *SIA 261 Actions on Structures, 2003 (Partial rev. 2014)*
- *EN 1991-2:2003 Actions on structures - Part 2: Traffic loads on bridges*

SIA 261 follows the general lines of EN 1991-2. Specific provisions are added/modified to adapt the EN 1991-2 provisions to Swiss standards/needs. This approach is followed by most European States that have adopted the Eurocodes, via National Annexes.

EN 1991-2:2003, Section 4.1 “Field of application” includes the following statements:
“Load models defined in this section should be used for the design of road bridges with loaded lengths less than 200 m. […] 200 m corresponds to the maximum length taken into account for the calibration of Load Model 1. In general, the use of Load Model 1 is safe-sided for loaded lengths over 200 m.”

Typically, new designs of bridges with spans longer than 200 m use the load models in SIA/Eurocode (or the corresponding governing code) in lieu of developing project-specific criteria. However, in the case of assessment of existing long-span bridges, where adoption of these load models could result in costly upgrades or the need for complete replacement of the bridge, it is more common to develop project-specific load models based on measured traffic patterns.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Non-motorised traffic

- Covered in SIA 261, Chapter 9
- Structures covered include:
  1. Pedestrian and cycle path bridges
  2. Bridges at train stations across rail lines
  3. Piers
  4. Walkways on road bridges
  5. Service gangways

1

2

3

4

5

Notes:

See also: EN 1991-2:2003, Section 5: Actions on footways, cycle tracks and footbridges.

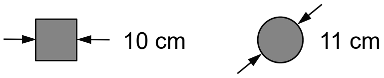
Photo Credits:

1. https://www.viator.com/de-CH/tours/Danang/Ba-Na-Hills-and-Golden-Bridge-Tour-Da-Nang-Full-Day/d4680-92163P65
2. https://koegenu.dk/details-page/news/kom-til-stor-aabningsfest-for-koege-nord-station.56559
3. https://www.californiabeaches.com/piers-in-san-diego-ca/
4. https://choosingfigs.com/183-walk-across-brooklyn-bridge/
5. https://www.oilandgaspeople.com/news/4430/offshore-workers-walk-to-work-with-ampelmann/

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Non-motorised traffic

- Two, independent, non-simultaneously acting load models are considered
- Load Model 1 (crowd of people)
  - Uniformly distributed load q_k = 4.0 kN/m^2
  - Placed in most unfavourable position
- Load Model 2 (*lightweight* maintenance vehicle)
  - Concentrated load Q_k = 10 kN
  - Acting in most unfavourable position, on quadratic / circular bearing area:



- Horizontal Load for footbridges:
  - Acts in longitudinal axis of bridge at surfacing level (together with vertical live load)
  - Max. { 10% $\sum q_k$ or 60% Q_k }

Maximum Credible Loading

2.4 kN/m^2 (50 psf) | 4.8 kN/m^2 (100 psf) | 7.2 kN/m^2 (150 psf)

Comparison to other codes:

- Uniform Loading:

The SIA-specified characteristic uniform load of 4.0 kN/m^2 combined with a load factor of 1.5 results in a design load of 6.0 kN/m^2.

EN 1991-2:2003 recommends the use of a characteristic uniform load of 5.0 kN/m^2 for the portion of road bridges subjected to pedestrian or cycle traffic. Combined with a load factor of 1.5 this results in a design load of 7.5 kN/m^2. This characteristic uniform load is also recommended in the case of footbridges subjected to crowd loading. Otherwise the characteristic uniform load can be determined as a function of the loaded length, L (m), as follows: 2.5 kN/m^2 ≤ 2.0 + 120/(L + 30) ≤ 5.0 kN/m^2. For a loaded length of 30 m, the corresponding load is 4.0 kN/m^2.

For large footbridges (e.g. more than 6 m width) it is noted that project specific load models may need to be defined to better capture the activities that may take place on such a bridge.

It is noted that loads due to cycle traffic are generally much lower than those for pedestrian traffic, while special considerations may need to be given to loads due to horses or cattle for individual projects.

The AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges specify a uniform pedestrian loading of 4.3 kN/m^2 (90 psf) combined with a load factor of 1.75, resulting in a design load of 7.5 kN/m^2.

For comparison, the maximum credible pedestrian loading appears to be around 7.2 kN/m^2 (150 psf) (Nowak, 2000)

(continued on following slide)

References/Photo Credits:

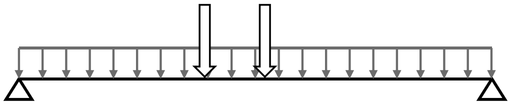
AASHTO (2009), LRFD Guide Specifications for the Design of Pedestrian Bridges

Nowak, A. S. and K. R. Collins. 2000. Reliability of Structures, McGraw-Hill International Editions, Civil Engineering Series. The McGraw-Hill Companies, Singapore.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Road traffic

- Covered in SIA 261, Chapter 10
- Only normal use by road traffic is covered
- Special vehicles not covered
- For L > 200 m, special investigations may be warranted
- Traffic loads typically idealised as:
  1. Concentrated axle loads representing heavy vehicles (trucks / lorries)
  2. Uniformly distributed loads representing heavy traffic (trucks) on one lane and light vehicles (cars) and the remaining lanes



Notes:

See also: EN 1991-2:2003, Section 4: Road traffic actions and other actions specifically for road bridges.

Photo Credit:
https://www.sfchronicle.com/news/article/Several-lanes-of-westbound-Bay-Bridge-closed-in-6707112.php

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(continued from previous slide)

- Concentrated Loading (Service Vehicle):

In lieu of project-specific provisions, EN 1991-2:2003 recommends the following model for a service vehicle: A two-axle load group of 80 and 40 kN, separated by a wheel base of 3 m, with a track (wheel-centre to wheel-centre) of 1.3 m and square contact areas of side 20 cm. The braking force associated with this model should be 60% of the vertical load. Therefore, the maximum considered concentrated load per wheel is 40 kN, i.e. 4 times higher than what is specified by SIA (also distributed over 4 times the bearing area). The same load model is recommended for use to account for accidental presence of vehicle on the bridge in case no permanent obstacle prevents such an occurrence.

The AASHTO LRFD Guide Specifications for the Design of Pedestrian Bridges specify the following model for a maintenance vehicle: A two-axle load group, separated by a wheel base of 4.3 m, with a track (wheel-centre to wheel-centre) of 1.8 m. The axle loads depend on the clear deck width. For widths between 2.1 to 3.0 m, the axle weights are 9 and 36 kN, while for widths over 3.0 m, the axle weights are 18 and 72 kN.

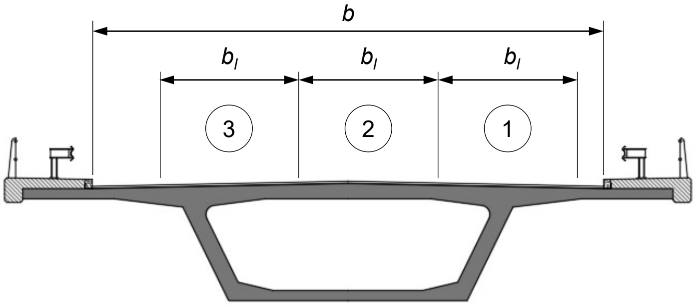
Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Road traffic

Division of roadway:

1. Define roadway width, *b*
2. Divide the roadway width into notional (fictitious) lanes according to table
3. Locate & number the notional lanes:
   - Depends on type of verification
   - Maximise effects of loading
   - Most unfavourable effect → Lane Number 1, second most unfavourable effect → Lane Number 2, etc.

Note: Influence lines help identifying the governing load positions



Roadway width b	**Number of notional lanes**	**Width of a notional lane b_l**	**Width of the remaining area**
$b < 5.4$ m	$n_l = 1$	3 m	b – 3 m
5.4 m ≤ b < 6 m	$n_l = 2$	b / 2	0
6 m ≤ b	n_l = Int [b / (3 m)]	3 m	b – (3 m) x n_l

Notes:

The roadway width, *b*, should be measured between kerbs or between the inner limits of vehicle restraint systems, and should not include the distance between fixed vehicle restraint systems or kerbs of a central reservation nor the widths of these vehicle restraint systems.

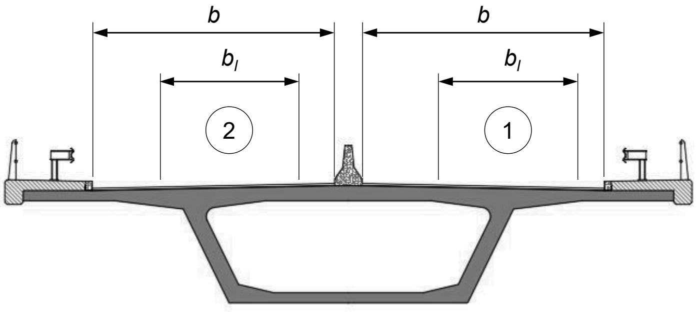
Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Road traffic

Division of roadway – Special Cases:

Separated roadways on common superstructure:

- If separation is permanent, each part of the roadway may be considered separately (for division into notional lanes), but numbering of notional lanes is continuous, i.e. there is only one Lane Number 1
- However, to account for future modifications, it is common to ignore the median barrier when defining notional lanes → conservative



Design Criteria – Structural Safety and Serviceability: Actions

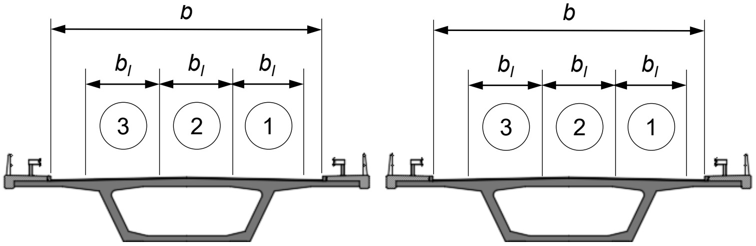
Live Loads – Road traffic

Division of roadway – Special Cases:

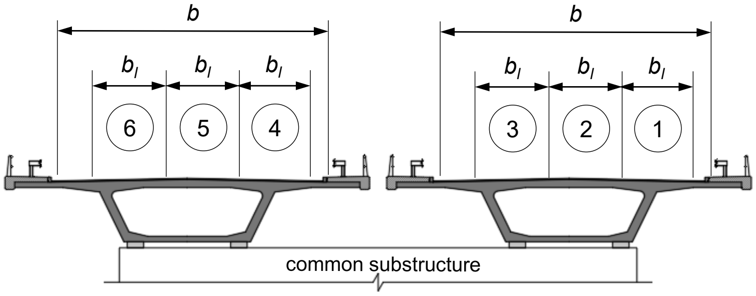
Separated roadways on independent superstructures:

- Each superstructure is considered separately, i.e. lane numbering is not continuous (two lanes Number 1).
- If substructure is common for both superstructures, numbering of notional lanes is continuous, i.e. there is only one Lane Number 1 for the design of the substructure elements.

Notional lanes for superstructure design:



Notional lanes for substructure design:



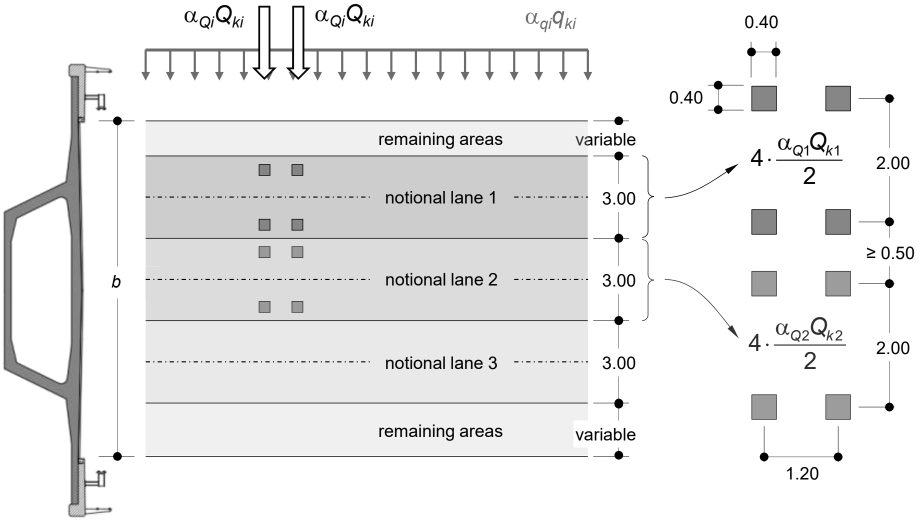
Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Road traffic

Application of Traffic Loads:

Load Model 1 (LM1):

- Axle Loads
  Lane 1: Q_{k1} = 300 kN
  Lane 2: Q_{k2} = 200 kN
- Uniformly distributed load
  Lane 1: q_{k1} = 9.0 kN/m^2
  Elsewhere: q_k = 2.5 kN/m^2
  (including remaining areas)
- α factors:
  Account for composition & density of traffic
  Normally: $\alpha_Q = \alpha_q = 0.9$



[Dimensions in m]

Notes:

Load Model 1:

In the notional (fictitious) lanes, axle groups each consisting of two axles arranged symmetrically with respect to the lanes shall be assumed. The axle load is imposed on the structure by two equally bearing wheels, with a quadratic bearing surface. The axle groups in the notional lanes 1 & 2 may be assumed to act in the same cross-section. In addition to the axle groups, a uniformly distributed load over the entire roadway area shall be assumed. Notional lane 1 carries a higher distributed load than the remaining lanes/areas.

For the determination of local stresses, the axle groups shall be arranged asymmetrically to the axis of the lanes.

The loading as well as the numbering and arrangement of the notional lanes shall be chosen such that in the corresponding dimensioning situation the least favourable loading arrangement is obtained.

In cases of bridges of secondary importance with a roadway width up to 6 m, the α factors may be reduced after consultation with the owner and the supervisory authority. A value lower than 0.65 is not permitted.

In general dynamic effects are already taken into account in the load models. Specifically, in proximity to expansion joints an increase in axle loads due to increased dynamic action shall be considered. The increase is effective within a distance of 3 m from the expansion joint and is taken into account using an additional dynamic factor of Φ = 1.3.

Other load models: In addition to Load Model 1, SIA 261 specifies Load Model 3 which is used to model heavy transport vehicles on traffic routes for exceptional transports. For detailed information see SIA 261/1. EN 1991-2:2003, Section 4 specifies additional load modes (LM2 & LM4) which account for higher concentrated loads (LM2) and crowd loading (LM4).

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Road traffic

'Horizontal' Forces (only in combination with LM1):

Acceleration (QA) and braking (QB) forces:

- Modelled by 'horizontal' forces acting at the height of the roadway surface
- Correspond to the vertical loads of LM1 on Lane 1:

  $QA_k = QB_k = 1.2\ \alpha_{Q1}\ Q_{k1} + 0.1\ \alpha_{q1}\ q_{k1}\ b_1\ L$

  $QA_k = QB_k \leq 900$ kN

  where L = distance between expansion joints
- Act in the axis of Lane 1

  (For simplicity the line of action may be taken as the axis of the roadway, unless the eccentricity has a significant influence on the internal forces of the structure)

Centrifugal (QZ) and transverse forces:

- Generally of secondary importance in road bridges
- Centrifugal forces assumed to act in a radial direction at the height of the roadway surface:

Radius of curvature r	**QZ_k**
$r < 200$ m	$0.2\ Q_v$
$200 \text{ m} \leq r \leq 1500$ m	$Q_v\ (40 \text{ m} / r)$
$r > 1500$ m	0

where $Q_v = \sum \alpha_{Qi}\ (2Q_{ki})$ *[from LM1]*

- With the braking force QB_k acting in the longitudinal direction, a simultaneous transverse force of $0.25QB_k$ shall be assumed.

Notes:

The term 'Horizontal' is in quotes because in reality these forces act parallel/transverse to the axis of motion, i.e. the roadway alignment (profile grade & cross slope) needs to be taken into consideration.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Road traffic

Fatigue:

- Structural members subjected to load cycles shall be investigated for fatigue effects.
- Number of load cycles depends on:
  - Service (working) life of bridge

    Typically 70…75 years for new bridges (often, design is carried out for infinite fatigue life = Dauerfestigkeit)
  - Volume of traffic

    Indicative values below:

Road category	Example	Number of vehicles over 3.5 t per year and direction of traffic
1	national highways	2 000 000
2	main roads	500 000
3	collecting roads	125 000
4	access roads	50 000

- Only axle loads of Load Model 1, acting on notional Lane 1 shall be considered
- Transverse placement of the axle loads corresponds to the effective (driving) lane, not notional lanes.
- Longitudinally, axle loads are arranged in the most unfavourable positions to determine the maximum and minimum stresses for the considered member

Notes:

The influences of the expected volume of traffic, the load spectrum and the planned service (working) life can be taken into account using the operational load factor according to SIA 263 (Steel Structures).

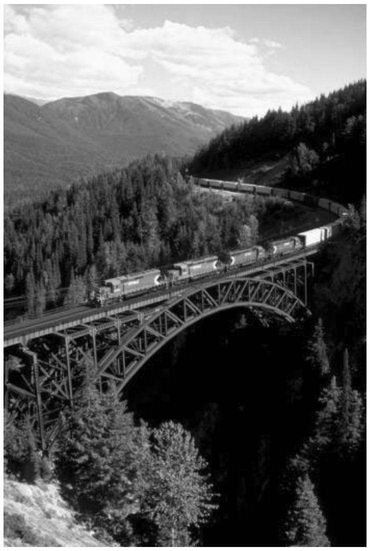
For traffic in both directions or for bridges with several separated traffic lanes, the partial operational load factor λ_4 shall be determined using the axle loads of the notional lane 1 for each additional lane.

In proximity to expansion joints an increase in axle load shall be considered as previously described in the definition of LM1.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Rail traffic

- Covered in SIA 261, Chapter 11 (and 12 for narrow gauge)
- Focus on Normal Gauge (1435 mm) rail, design speed ≤ 200 km/h (high speed and narrow gauge rail loads are similar in principle)
- Design based on planned number and position of tracks
- Account for:
  - Track deviations from planned position
  - Uneven distribution of axle loads on rails
- Service criteria agreement and basis of design shall specify (where applicable):
  - Alternative track positions (e.g. in railway station underpasses, consider tracks in any transverse position)
  - Loads models for trains not covered by code
  - Need for load tests
  - Load models and aerodynamic forces for V > 200 km/h



Notes:

See also: EN 1991-2:2003, Section 6: Rail traffic actions and other actions specifically for railway bridges.

Photo Credit:
https://en.m.wikipedia.org/wiki/Stoney_Creek_Bridge

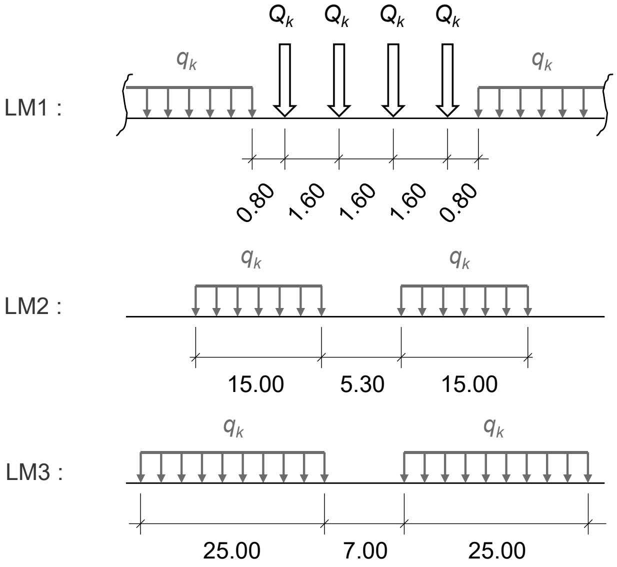
Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Rail traffic

Load Models (static effect)

- LM1 – normal rail traffic
- LM2 – normal rail traffic on continuous girders (to be applied only once per track)
- LM3 – heavy rail traffic (to be applied only once per structure, and only where applicable, to be decided by supervisory authority)

Load Model	Q_k [kN]	q_k [kN/m]
1	250	80
2	-	133
3	-	150



Notes:

To calculate earth pressures due to rail traffic beneath or adjacent to the tracks, Load Models 1, 2 or 3 may be distributed uniformly over a width of 3.0 m at a depth of 0.7 m below the top of the rails. The dynamic factor may be neglected.

Design Criteria – Structural Safety and Serviceability: Actions

- **Live Loads – Rail traffic:**

Acceleration (QA) and braking (QB) forces:

- Modelled by ‘horizontal’ forces acting in the axis of the track at the top of the rails
- Assumed uniformly distributed over length l [m] on which vertical rail traffic loads act:

Load Model	**QA_k [kN]**	**QB_k [kN]**
1	$33\ l \leq 1000$	$20\ l \leq 6000$
2	$33\ l \leq 1000$	$20\ l$
3	$33\ l \leq 1000$	$35\ l$

- For special construction (sliding platforms, moveable bridges) values shall be increased by 25%
- For structures with $l > 300$ m, QA_k & QB_k shall be specified through consultation with the supervisory authority

Nosing force (Schlingerkraft QS):

- Accounts for effect of lateral impacts caused by nosing of the vehicle
- Modelled by ‘horizontal’ concentrated force acting in the most unfavourable position, at the top of the rails, perpendicular to the axis of the track:
- $QS_k = 100$ kN

Notes:

The term ‘Horizontal’ is in quotes because in reality these forces act parallel/transverse to the axis of motion, i.e. the railway alignment needs to be taken into consideration.

Design Criteria – Structural Safety and Serviceability: Actions

- **Live Loads – Rail traffic:**

  Centrifugal forces (QZ, qZ):

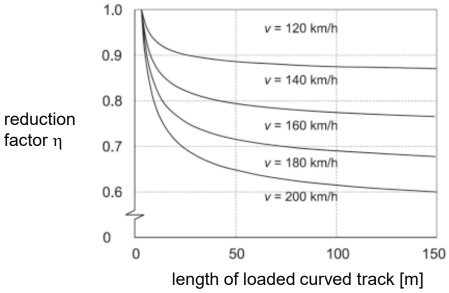
  - Considered in the case of curved track sections
  - Assumed to act in a radial direction, 1.8 m above the top of the rails
  - Characteristic values are a function of the vertical rail traffic loads (for all load models):

$$QZ_k = \frac{\eta v^2 Q_k}{rg} \qquad qZ_k = \frac{\eta v^2 q_k}{rg}$$

  where:

  - g = acceleration of gravity (9.81 m/s^2)
  - r = radius of curvature (m)
  - v = design speed (m/s)
  - η = reduction factor if v > 120 km/h

- Design speed specified by supervisory authority
- For LM3, $v \leq 80$ km/h (= 22.2 m/s)
- For $v > 120$ km/h, check for:
  - Full loads LM1 or LM2 with *QZ* & *qZ* for $v = 120$ km/h
  - LM1 or LM2 multiplied by η together with corresp. *QZ* & *qZ* forces for specified $v > 120$ km/h



Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Rail traffic

Dynamic Factor

Accounts for track/vehicle imperfections

$$\Phi = \frac{1.44}{\sqrt{l_\Phi} - 0.2} + 0.82 \qquad 1 \leq \Phi \leq 1.67$$

where l_Φ (m), the decisive length (table 15 of SIA 261)

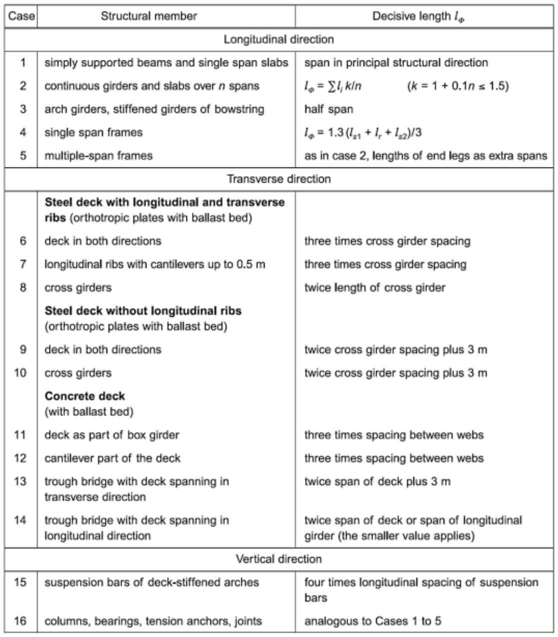
For arch and concrete bridges with cover > 1 m, Φ can be reduced:

$$\Phi_{\text{red}} = \Phi - \frac{h-1}{10} \geq 1$$

where h (m), denotes the cover including the ballast.

For columns with a slenderness ratio < 30, abutments, foundations, retaining walls and ground pressures:

$\Phi = 1$



Case	Structural member	Decisive length l_Φ
	Longitudinal direction	
1	simply supported beams and single span slabs	span in principal structural direction
2	continuous girders and slabs over *n* spans	$l_\Phi = \sum l_i \, k/n \qquad (k = 1 + 0.1n \leq 1.5)$
3	arch girders, stiffened girders of bowstring	half span
4	single span frames	$l_\Phi = 1.3\,(l_{s1} + l_r + l_{s2})/3$
5	multiple-span frames	as in case 2, lengths of end legs as extra spans
	Transverse direction	
	Steel deck with longitudinal and transverse ribs (orthotropic plates with ballast bed)	
6	deck in both directions	three times cross girder spacing
7	longitudinal ribs with cantilevers up to 0.5 m	three times cross girder spacing
8	cross girders	twice length of cross girder
	Steel deck without longitudinal ribs (orthotropic plates with ballast bed)	
9	deck in both directions	twice cross girder spacing plus 3 m
10	cross girders	twice cross girder spacing plus 3 m
	Concrete deck (with ballast bed)	
11	deck as part of box girder	three times spacing between webs
12	cantilever part of the deck	three times spacing between webs
13	trough bridge with deck spanning in transverse direction	twice span of deck plus 3 m
14	trough bridge with deck spanning in longitudinal direction	twice span of deck or span of longitudinal girder (the smaller value applies)
	Vertical direction	
15	suspension bars of deck-stiffened arches	four times longitudinal spacing of suspension bars
16	columns, bearings, tension anchors, joints	analogous to Cases 1 to 5

Notes:

See SIA 261, Chapter 11, Table 15: Decisive lengths to determine dynamic factors.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Rail traffic

Factor for the classification of standard load models

Accounts for composition of rail traffic

Normal case α = 1.33

Existing bridges α = 1.00

Applies to:

- LM1 & LM2 loads
- Acceleration forces
- Braking forces
- Centrifugal forces
- Nosing forces
- Earth pressures due to rail traffic

- **Live Loads – Rail traffic**

Groups of actions

All actions shall be considered in groups as follows:

- For bridges with 2 tracks, consider:
  - LM1 or LM2 on both tracks
  - LM1 on one track & LM2 on the other track
  - LM3 on one track & LM1/LM2 on the other track

- For bridges with ≥ 3 tracks, actions shall be specified in consultation with the supervisory authority.

- Consider most unfavourable effect of:
  - 100% (QA or QB) + 50% (QS, QZ, qZ)
  - 50% (QA or QB) + 100% (QS, QZ, qZ)

Notes:

Reduced values for the classification factor, α, may be used (not less than 1.0) through consultation with the supervisory authority provided this is based on appropriate investigations.

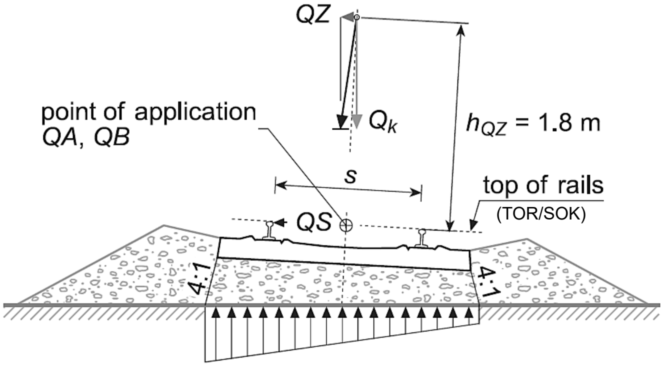
Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Rail traffic

Load eccentricity

The following accidental eccentricities shall be considered:

- For bridges with ballast, consider deviation of track axis from planned position of ± 100 mm.
- For LM1 & LM2, consider eccentricity of axle load of 1/18 of track width (80 mm) to account for non-uniform loading of rail vehicles.
- Consider eccentricities due to track cant according to the following sketch:



Point of application and actions

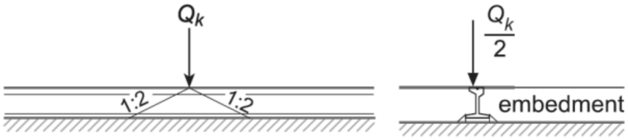
Top of rails (TOR) = Schienenoberkante (SOK)

Design Criteria – Structural Safety and Serviceability: Actions

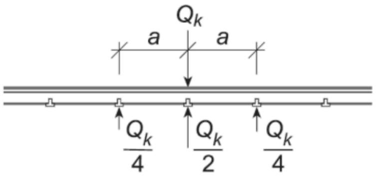
Live Loads – Rail traffic

Load distribution

May be considered according to the following sketches:

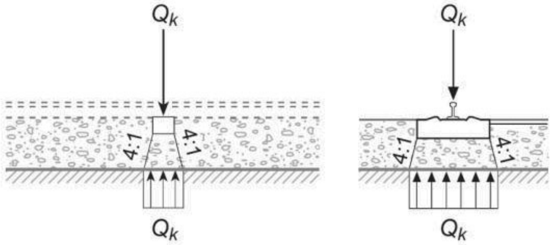


Grooved rail embedded in concrete



a = distance between rail support points

Rail supported on sleepers



Sleepers supported on ballast bed

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Rail traffic

Fatigue

- Structural members of railway bridges subjected to alternating loads shall be investigated for fatigue
- Number of loaded cycles depends on:
  - Service (working) life of bridge

    Typically 100 years for new bridges (often, design is carried out for infinite fatigue life = Dauerfestigkeit)
  - Traffic volume

    Indicative values below:

Traffic composition	**Number of trains per day and per track**	**Annual tonnage per track**
regional traffic	≤ 120	≤ 25 000 000
standard traffic	≤ 120	≤ 25 000 000
heavy traffic with 25 t axle loads	> 120	> 25 000 000

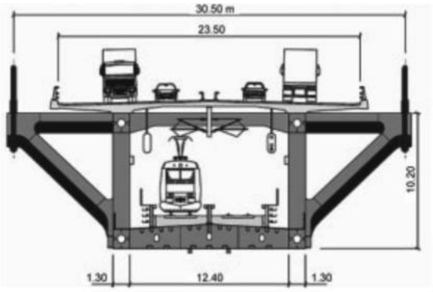
- Fatigue load model
  - LM1 shall be used
  - Q_k & q_k values multiplied with Φ and α factors
  - QZ & qZ shall be considered with $\alpha = 1$
  - For > 3 tracks, fatigue LM shall be applied to 2 tracks max.
  - In special cases, fatigue may be verified using special load models subject to the approval of the supervisory authority.

Design Criteria – Structural Safety and Serviceability: Actions

Live Loads – Combined Road & Rail traffic

- Bridges simultaneously subjected to road and rail traffic loads shall be dimensioned for the more unfavourable of the following situations:
  - whole traffic surface subjected to road vehicle loading
  - rail traffic loads on track areas, road vehicle loading on remaining traffic areas

- For longer spans / major links, it is common to use double deck solutions to separate road from rail traffic
  → full combination possible
  → load combinations to be agreed with owner
  (service criteria agreement)

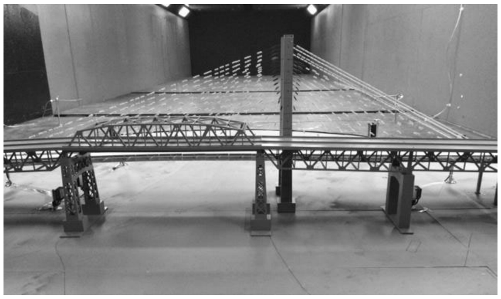


References/Image Credits:

https://www.bbc.com/news/world-europe-35159183
https://www.researchgate.net/figure/Oresund-Bridge-Sweden-Denmark-15_fig7_281280573

Design Criteria – Structural Safety and Serviceability: Actions

- **Wind Loads:**
  - Covered in SIA 261, Chapter 6. These provisions
    … apply to bridges with negligible dynamic response, i.e. generally road and rail bridges of spans up to 40 m (see also notes).
    … can be adapted to cover longer span and cable-supported bridges with input from wind specialists
  - Wind tunnel tests are typically required for long span bridges
  - Wind forces are generally assumed to act normal to the surface under consideration
  - Effects to be considered:
    … increase of exposed area due to simultaneous actions such as traffic load, snow or ice accretion
    … interaction with adjacent structures
    … influence of wind-induced vibrations on fatigue life



Wind tunnel testing on a new cable-stayed bridge; the presence of an existing truss bridge is accounted for, in order to capture potential interaction between the bridges.

See also:
… SIA 261/1, Section 10 (Wind, dynamic behaviour of structures)
… SIA Documentation D0188
… EN 1991-1-4:2007, Actions on Structures, Part 1-4: General Actions – Wind Actions; Section 8: Wind actions on bridges

Photo Credit:

https://www.dot.ny.gov/kbridge/photos-may2015

Design Criteria – Structural Safety and Serviceability: Actions

- **Wind Loads:**
  - Dynamic Pressure, q_p

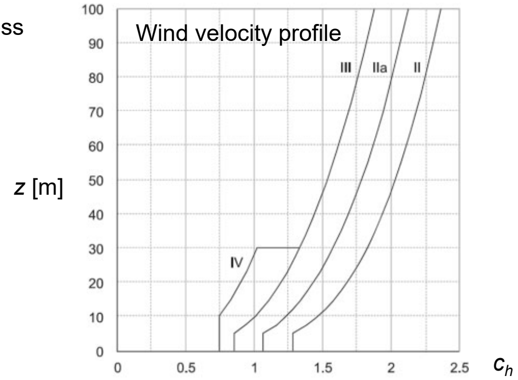
$$q_p = q_{p0} \cdot c_h \longrightarrow c_h = 1.6\left[\left(\frac{z}{z_g}\right)^{\alpha_r} + 0.375\right]^2$$

height

terrain roughness

gradient height

reference value – taken from map:
(General: 0.9…1.3 kPa / Alps: 1.1…3.3 kPa)



Terrain category	Examples	z_g [m]	α_r
II	lakeside	300	0.16
IIa	large plain	380	0.19
III	villages, free field	450	0.23
IV	large urban area	526	0.30

Notes:

The reference value of the dynamic pressure q_{p0} shall be taken into account according to SIA 261, Appendix E. It corresponds to the peak velocity (with gusts of a few seconds) for z = 10 m and terrain category III. Its return period equals 50 years.
For structures in locations with extreme wind conditions, for example, mountain peaks and ridges, and hillsides, an increase of q_{p0} shall be considered on an individual basis.

Design Criteria – Structural Safety and Serviceability: Actions

- **Wind Loads:**
  - Wind forces, Q_1 (horizontal) & Q_3 (vertical)

Reduction factor =
$\begin{cases} 1.0 \text{ for superstructure} \\ \text{for substructure:} \end{cases}$

$$Q_{k,1/3} = c_{red}\ c_d\ c_{f,1/3}\ q_p\ A_{ref}$$

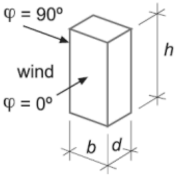
reference area for considered surface

dynamic factor

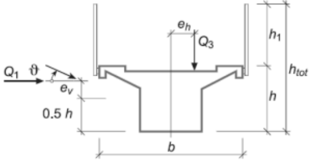
(1.0 for short to moderate span bridges, see notes)

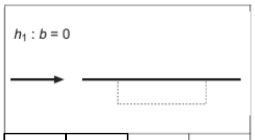
force factors:

dynamic pressure

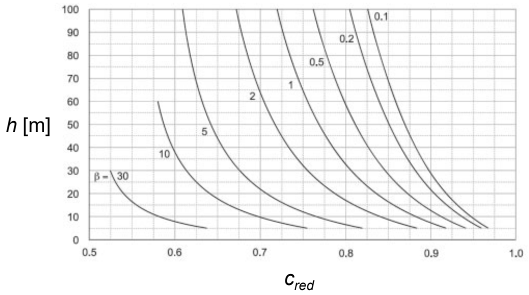


$\beta = \frac{b}{h}$ or $\frac{d}{h}$





		c_{f1}	c_{f3}	e_v/h	e_h/b
	ϑ	$l \cdot h_{tot}$	$l \cdot b$	h	b
$h : b = 0.110$ 	0°	1.45	0.32	−0.27	−0.09
	−6°	1.45	−0.34	1.41	−0.26
	−10°	1.55	−0.79	0.59	−0.20



Notes:

The reduction factor c_{red} takes into account the influence of the spatial distribution of the wind pressures and taken equal to 1.0 for bridge superstructures.

The dynamic factor c_d takes into account the increase due to dynamic resonance effects of the structure caused by turbulence in the wind direction. It depends on the eigenfrequency, mode shapes and damping of the structure. The design code SIA 261/1 provides the following criterion for using =1.0:

$$\frac{m \cdot \xi}{\rho \cdot d^2} > 1.9$$

where m = average mass per unit length in kg/m, ρ = air density = 1.2 kg/m^3, d = equivalent diameter of structure idealised as a beam and ξ = mechanical damping ratio, see Table 18 of SIA 261/1:

… prestressed/uncracked concrete and steel-concrete composite bridges ξ = 0.006

… cracked concrete bridges ξ = 0.015

… welded steel truss bridges ξ = 0.003

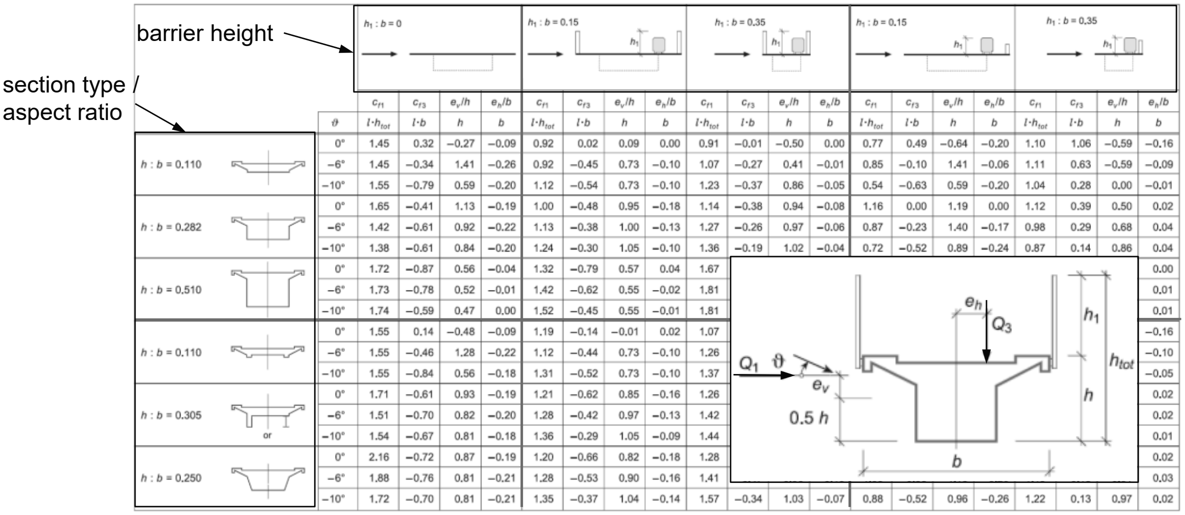
… bolted steel truss bridges ξ = 0.005 (if bolts are not preloaded: 0.008)

… timber bridges ξ = 0.01 … 0.02

In other cases, and c_d be determined e.g. from to the SIA documentation SIA D 0188 or EN 1991-1-4.

Design Criteria – Structural Safety and Serviceability: Actions

- **Wind Loads:**
  - Wind forces, Q_1 (horizontal) & Q_3 (vertical) – Force Factors and Eccentricities (Appendix C)



		$h_1 : b = 0$				$h_1 : b = 0.15$				$h_1 : b = 0.35$				$h_1 : b = 0.15$				$h_1 : b = 0.35$			
		c_{f1}	c_{f3}	e_v/h	e_h/b	c_{f1}	c_{f3}	e_v/h	e_h/b	c_{f1}	c_{f3}	e_v/h	e_h/b	c_{f1}	c_{f3}	e_v/h	e_h/b	c_{f1}	c_{f3}	e_v/h	e_h/b
	ϑ	$l \cdot h_{tot}$	$l \cdot b$	h	b	$l \cdot h_{tot}$	$l \cdot b$	h	b	$l \cdot h_{tot}$	$l \cdot b$	h	b	$l \cdot h_{tot}$	$l \cdot b$	h	b	$l \cdot h_{tot}$	$l \cdot b$	h	b
$h : b = 0.110$	0°	1.45	0.32	−0.27	−0.09	0.92	0.02	0.09	0.00	0.91	−0.01	−0.50	0.00	0.77	0.49	−0.64	−0.20	1.10	1.06	−0.59	−0.16
	−6°	1.45	−0.34	1.41	−0.26	0.92	−0.45	0.73	−0.10	1.07	−0.27	0.41	−0.01	0.85	−0.10	1.41	−0.06	1.11	0.63	−0.59	−0.09
	−10°	1.55	−0.79	0.59	−0.20	1.12	−0.54	0.73	−0.10	1.23	−0.37	0.86	−0.05	0.54	−0.63	0.59	−0.20	1.04	0.28	0.00	−0.01
$h : b = 0.282$	0°	1.65	−0.41	1.13	−0.19	1.00	−0.48	0.95	−0.18	1.14	−0.38	0.94	−0.08	1.16	0.00	1.19	0.00	1.12	0.39	0.50	0.02
	−6°	1.42	−0.61	0.92	−0.22	1.13	−0.38	1.00	−0.13	1.27	−0.26	0.97	−0.06	0.87	−0.23	1.40	−0.17	0.98	0.29	0.68	0.04
	−10°	1.38	−0.61	0.84	−0.20	1.24	−0.30	1.05	−0.10	1.36	−0.19	1.02	−0.04	0.72	−0.52	0.89	−0.24	0.87	0.14	0.86	0.04
$h : b = 0.510$	0°	1.72	−0.87	0.56	−0.04	1.32	−0.79	0.57	0.04	1.67											0.00
	−6°	1.73	−0.78	0.52	−0.01	1.42	−0.62	0.55	−0.02	1.81											0.01
	−10°	1.74	−0.59	0.47	0.00	1.52	−0.45	0.55	−0.01	1.81											0.01
$h : b = 0.110$	0°	1.55	0.14	−0.48	−0.09	1.19	−0.14	−0.01	0.02	1.07											−0.16
	−6°	1.55	−0.46	1.28	−0.22	1.12	−0.44	0.73	−0.10	1.26											−0.10
	−10°	1.55	−0.84	0.56	−0.18	1.31	−0.52	0.73	−0.10	1.37											−0.05
$h : b = 0.305$ or	0°	1.71	−0.61	0.93	−0.19	1.21	−0.62	0.85	−0.16	1.26											0.02
	−6°	1.51	−0.70	0.82	−0.20	1.28	−0.42	0.97	−0.13	1.42											0.02
	−10°	1.54	−0.67	0.81	−0.18	1.36	−0.29	1.05	−0.09	1.44											0.01
$h : b = 0.250$	0°	2.16	−0.72	0.87	−0.19	1.20	−0.66	0.82	−0.18	1.28											0.02
	−6°	1.88	−0.76	0.81	−0.21	1.28	−0.53	0.90	−0.16	1.41											0.03
	−10°	1.72	−0.70	0.81	−0.21	1.35	−0.37	1.04	−0.14	1.57	−0.34	1.03	−0.07	0.88	−0.52	0.96	−0.26	1.22	0.13	0.97	0.02

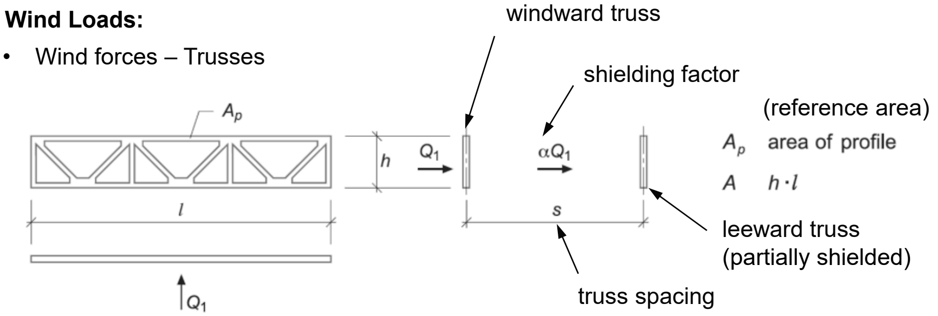
Notes:

SIA 261, Appendix C, Table 63 specifies force factors, c_f, for the horizontal and vertical components of the wind forces, along with the respective force eccentricities. The parameters under consideration include:

- The cross section type (closed vs. open) and shape (vertical vs. inclined webs)
- The cross section aspect ratio
- The presence of barriers and vehicles and their relative height to the cross section width.
- The wind direction with respect to horizontal.

Design Criteria – Structural Safety and Serviceability: Actions

- **Wind Loads:**
  - Wind forces – Trusses



windward truss

shielding factor

(reference area)

leeward truss
(partially shielded)

truss spacing

Force factor, c_{f1}

A_p / A	c_{f1}
0.01	2.0
0.1	1.9
0.15	1.8
0.2	1.7
0.3…0.8	1.6
0.95	1.8
1.0	2.0

Reduction factor, c_{red}

A_p / A	0.25	0.5	0.9	0.95	1.0
l / h = 5	0.96	0.91	0.87	0.77	0.6
l / h = 20	0.98	0.97	0.94	0.89	0.75
l / h = 50	0.99	0.98	0.97	0.95	0.9
l / h = ∞	1.0	1.0	1.0	1.0	1.0

Shielding factor, α

A_p / A	0.1	0.2	0.3	0.4	0.5	0.6…1.0
s / h = 0.5	0.93	0.75	0.56	0.38	0.19	0
s / h = 1	0.99	0.81	0.65	0.48	0.32	0.15
s / h = 2	1.0	0.87	0.73	0.59	0.44	0.3
s / h = 4	1.0	0.9	0.78	0.65	0.52	0.4
s / h = 6	1.0	0.93	0.83	0.72	0.61	0.5

Notes:

SIA 261, Appendix C, Table 75 provides guidance on how to treat superstructures with porous surfaces, such as trusses. Similar concepts may be used for arch bridges. For long span trusses and arches this approach should only used for predimensioning purposes. Final design should be based on input from a wind specialist.

Design Criteria – Structural Safety and Serviceability: Actions

- **Wind Loads:**
  - Wind forces – Cables

    Force factors for wires, bars, tubes and cables with l / d ≥ 100

$d\sqrt{q_p}$ ← kPa	Global force factors c_f			
	reference area = $d \cdot l$ (d = diameter, l = length, both in m)			
≤ 0.3	1.2	1.2	1.2	1.3
> 0.3	0.5	0.7	0.9	1.1
	 smooth wires, bars and tubes	 medium rough wires and bars	 fine-stranded power and suspension cables	 coarse-stranded power and suspension cables

Notes:

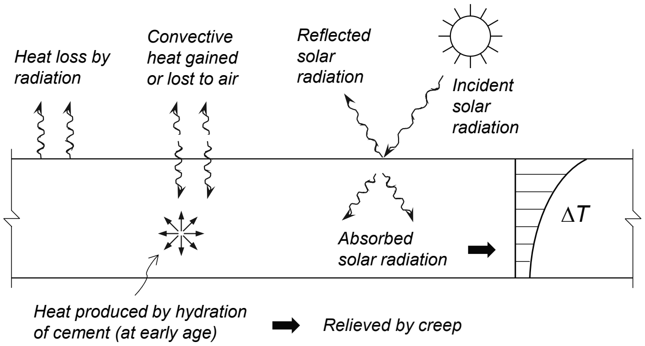
SIA 261, Appendix C, Table 74 provides guidance on how to treat wind forces on cables, e.g. stay-cables, suspension cables, vertical hangers. For long cables this approach should only used for preliminary dimensioning purposes. Final design should be based on input from a wind specialist, including an assessment on rain-wind induced vibrations and the need to provide supplemental damping.

Design Criteria – Structural Safety and Serviceability: Actions

- **Temperature Effects:**
  - Covered in SIA 261, Chapter 7
  - Only climatic effects are addressed
  - Temperature variations lead to deformations
  - Restrained deformations lead to stresses

→ Basically, the designer may choose to
… accomodate deformations or
… design for restraint stresses

→ see Support and Articulation chapter (jointed bridges vs. integral and semi-integral bridges)



Heat transfer processes for a bridge deck in daytime in summer [after Ghali et al, 2002]

temperature variation

$$\varepsilon_T = \alpha_T \, \Delta T$$

strain due to temperature variation

coefficient of thermal expansion
= 10^{-5} / °C for concrete & steel

Notes:

Restrained deformations due to temperature differences may cause high stresses: A fully restrained temperature difference of 20°C would cause stresses of roughly 40 MPa in steel structures, or 7 MPa in concrete structures. These stresses are of the same order of magnitude as stresses due to dead loads and live loads. However, deformations of bridge girders are never fully restrained.

Rather, as further outlined in the Support and Articulation chapter:

(i) In jointed bridges, the superstructure is often articulated such that the deformations caused by the uniform variation component (ΔT_1) – expansion and contraction of the superstructure along its axis – can be accommodated without generating restraint (except for bearing friction)

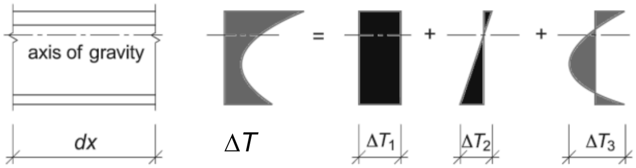
(ii) In integral and semi-integral bridges (monolithic connections at the abutments and/or intermediate piers), deformations of the superstructure are restrained by the substructure. However, since the axial stiffness of the bridge girder is much higher than the stiffness of the substructure
… only a small portion (usually less than 10%) of the full restraint is generated
… the substructure must be designed to accommodate almost the full, free thermal deformations

In concrete structures, restraint stresses are further reduced by cracking since the cracked elastic stiffness is much lower than uncracked stiffness. Usually, a minimum reinforcement for crack width control is provided, even if the elements are expected to remain uncracked (such as e.g. fully prestressed concrete bridge girders). For more details, see e.g. Stahlbeton I, Tension Chord Model.

Uniform temperature variation of the substructure elements also causes deformations. However, these can typically be neglected.

Design Criteria – Structural Safety and Serviceability: Actions

- **Temperature Effects:**
  - Components of temperature variation:
    → Uniform (ΔT_1) – variation from mean
    → Linear (ΔT_2) – one-sided warming/cooling
    → Non-linear (ΔT_3) (usually ignored – see next slide)



Type of construction	**ΔT_{1k} [°C]**
plain concrete	± 15
reinforced and prestressed concrete	± 20
steel	± 30
composite steel-concrete	± 25

Type of bridge	**Warm upper surface ΔT_{2k} [°C]**	**Cold upper surface ΔT_{2k} [°C]**
steel bridges	+ 10	- 6
concrete bridges		
h ≤ 1.0 m	+12	- 4
h ≥ 3.0 m	+8	- 3
composite bridges		
concrete slab	+12	- 4
steel girder	0	0

h = height of cross-section

Notes:

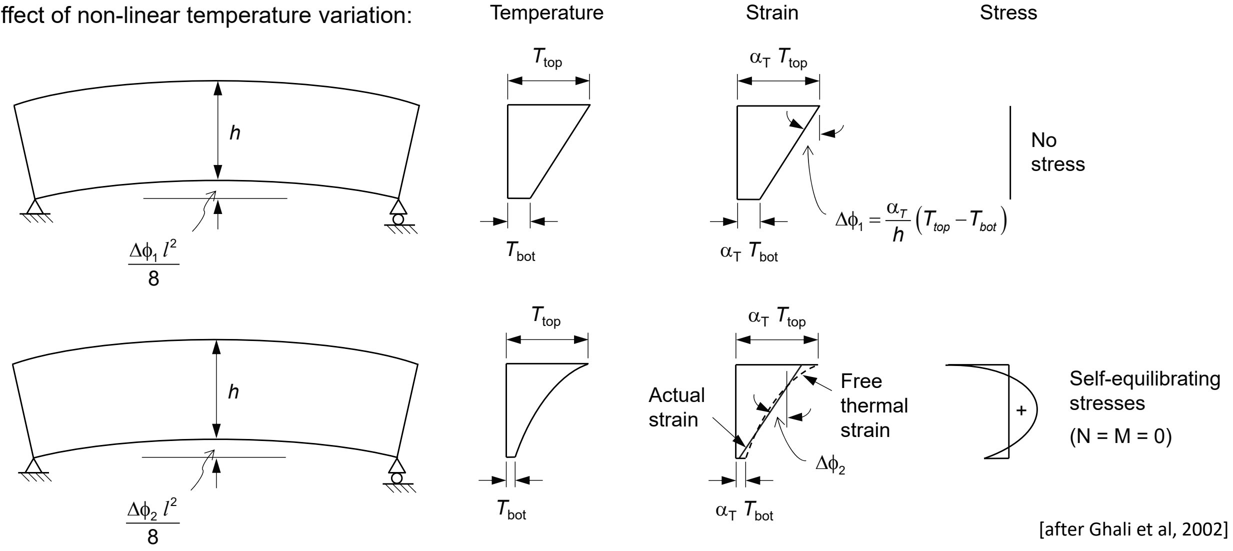
In the case of cable-supported bridges (cable-stayed, suspension, network arches), the difference in the rate of warming/cooling of the cables compared to the concrete and steel elements of the bridge is captured by assuming a differential temperature between the cables and the remaining elements.

The linear variation component (ΔT_2) is typically considered only for superstructures and in the vertical direction. Unlike restraint forces caused by uniform temperature changes, that generally need to be accounted for in the design of integral bridge girders (combined action of bending and axial tension, see Support and Articulation – Integral and Semi-Integral Bridges), temperature variation may be neglected in the ultimate limit state design of ductile bridge girders (such as concrete girders with $x/d < 0.35$), similar to imposed deformations caused by support settlements, according to the lower bound theorem of plasticity theory. Temperature variation must however be accounted for in the design of non-ductile superstructures, as well as in serviceability and fatigue verifications.

Furthermore, in the case of tall substructure elements, and in particular towers of cable-stayed and suspension bridges, the linear variation component should also be considered to capture one-sided warming/cooling of these elements (not limited to, but particularly during construction, since the associated curvatures may severely affect the vertical alignment of cantilevered sections). This also applies to the ribs of arch bridges.

Design Criteria – Structural Safety and Serviceability: Actions

- **Temperature Effects:**
  - Effect of non-linear temperature variation:



[after Ghali et al, 2002]

Notes:

In a statically determinate system, linear temperature variation results in deformation (imposed curvature) but no internal stresses are developed. Each fibre undergoes its free thermal strain corresponding to the linear strain profile. Thereby, the underlying assumption of a linear strain distribution (“plane sections remain plane”) is implicitly satisfied.

In a statically determinate system, non-linear temperature variation results in internal self-equilibrating stresses, i.e. the individual fibres undergo tensile or compressive stresses, but no overall internal forces (stress-resultants) are caused. The internal stresses in each fibre correspond to the difference between their free thermal strain (i.e., if the fibres of the cross-section were independent) and the actual strain at the level of the fibre, which must satisfy the underlying assumption of a linear strain profile (“plane sections remain plane”) throughout the cross-section. The actual strain profile (mid-plane strain and curvature) is obtained by formulating the equilibrium conditions (zero normal force and bending moment), observing that the stresses in each fibre correspond to the *difference between the free thermal strain and the actual strain* (rather than just the actual strain as usual), multiplied by its elastic modulus E.

The same concept applies in the case of strains due to creep on a composite section, where the fibres in the steel section resist the tendency of the fibres in the concrete section to creep.

In a statically indeterminate system, any type of temperature variation results in deformation as well as internal forces due to compatibility.

Reference:

Ghali, Favre & Elbadry, “Concrete Structures – Stresses and Deformation,” Third Edition, Spon Press, London 2002.

Design Criteria – Structural Safety and Serviceability: Actions

- **Accidental (Extreme) Actions:**

  Covered in SIA 261 – see below for chapters

  Caused by human activity/error:
  - Vehicular impact (Ch. 14), Train derailment (Ch. 11 & 12)
  - Vessel impact
  - Explosion (Ch. 17), Fire (Ch. 15)

  Caused by nature:
  - Seismic (earthquake) loads (Ch. 16)
  - Avalanche load
  - Ice load

Photo Credits:

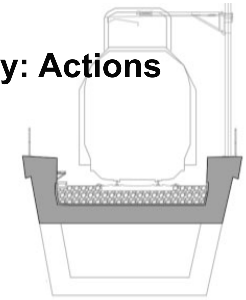
https://www.researchgate.net/figure/Collapse-of-a-bridge-due-to-vessel-impact-image-courtesy-of-Wikimedia-Commons-Xpda_fig8_272893388
https://www.reddit.com/r/CatastrophicFailure/comments/3pqopb/collapsed_highway_after_the_great_kobe_earthquake/
https://alchetron.com/Wenzhou-train-collision

Design Criteria – Structural Safety and Serviceability: Actions

The loads depend heavily on the use of the bridge

→ design of "footbridges" differs significantly from "bridges"

→ focus of lecture: road and railway bridges



Bridge use	**Pedestrian / Bicycle**	**Road** (α_Q=α_q=0.9)	**Railway** (α=1.33, Φ_{dyn}=1.67 for typ. deck)
Concentrated loads "Q"	low (service vehicles only) [CH: 10 kN]	high / var. position of vehicle axis [CH LM1: 4·α_Q·(150+100) kN = 900 kN]	very high / distributed by ballast [CH LM1: 4·α·Φ_{dyn}·250 kN = 2220 kN, per track]
Distributed loads "q"	moderate [CH: 4 kPa, full width]	moderate-high (on limited width) [CH LM1: α_q·9 kPa = 8.1 kPa, 3 m width]	high [CH LM1: α · Φ_{dyn}· 80 = 178 kN/m, per 3.80 m]
Longitudinal horizontal loads	low	moderate (braking / traction)	high (braking / traction)
Transverse horizontal loads	low	low-moderate (centrifugal)	moderate-high (centrifugal / nosing)
Fatigue	usually irrelevant	moderate (local elements)	highly relevant
Dynamic effects	slender bridges often sensitive to vibrations	included in traffic loads (most codes)	dynamic factor depending on structural element / dynamic analysis for high speed rail
Deflections (vertical)	moderate $w \leq l$ / 600 (LM1)	moderate $w \leq l$ / 500 (LM1)	highly relevant $w \leq l$ / 2000, v = 160 km/h (LM1-2)
Durability issues	moderate (de-icing)	high (de-icing, heavy load on joints)	low (no de-icing, joints not directly loaded)

The loads on a bridge deck depend heavily on the use of the bridge. Accordingly, the dimensioning of bridge decks differs significantly according to its use. In particular, the low traffic loads on footbridges allow much lighter solutions for the deck than those used in road and railway bridges.

Notes on table content:

- *The concentrated loads indicated are to be applied per deck on road bridges, per track on railway bridges*
- *The distributed loads indicated on road bridges have to be applied over a width of 3 m (fictitious traffic lane 1). On the remaining surface, a reduced load of α_q·2.5 kPa = 2.25 kPa has to be applied.*
- *An overload factor has to be applied on some railway lines*

Conceptual Design

Design Criteria – Structural Safety and Serviceability

Deformations

Verformungen

Design Criteria – Structural Safety and Serviceability: Deformations

- **Deflection limit criteria for Roadway bridges:**

  Covered in SIA 260 – Appendix B

  - Deflection calculation in accordance with corresponding material codes (SIA 262 to 266)
  - Project specific deflection limits may be agreed upon with the supervisory authority.
    - → Limits can be relaxed for secondary members
    - → Long span bridges (l > 200 m) require special attention

Limit State	**Consequences of effects of actions**		
	irreversible	reversible	reversible
	Load case		
	occasional	frequent	quasi-permanent
Functionality - vertical relative displacement at expansion joints		$\delta_v \leq 5$ mm $^{1)\,2)\,3)}$	
Comfort		$w \leq l \,/\, 500$ $^{4)}$	
Appearance			$w \leq l \,/\, 700$ $^{1)\,2)}$

Notes:
1) After deduction of camber. Consider long-term effects: CR + SH.
2) After installation of equipment.
3) Observe supplier guidelines.
4) Due to LM1.

Design Criteria – Structural Safety and Serviceability: Deformations

- **Deflection limit criteria for**
  Pedestrian and cycle-path bridges:

  Covered in SIA 260 – Appendix C

  - Deflection calculation in accordance with corresponding material codes (SIA 262 to 266)
  - Project specific deflection limits may be agreed upon with the supervisory authority.
    - → Limits can be relaxed for secondary members
    - → Long span bridges (l > 200 m) and flexible cable-supported or stress-ribbon bridges require special attention

Limit State	**Consequences of effects of actions**		
	irreversible	reversible	reversible
	Load case		
	occasional	frequent	quasi-permanent
Functionality - deflection within span - vertical relative displacement at expansion joints		$\delta_v \leq 5$ mm 1) 2) 3)	$w \leq l / 700$ 1) 2) 3)
Comfort		$w \leq l / 600$ 4)	
Appearance			$w \leq l / 700$ 1) 2)

Notes:
1) After deduction of camber. Consider long-term effects: CR + SH.
2) After installation of equipment.
3) Observe supplier guidelines.
4) Due to LM1.

Design Criteria – Structural Safety and Serviceability: Deformations

- **Deflection limit criteria for** **Normal gauge railway bridges:**

  Covered in SIA 260 – Appendix D
  - Deflection calculation in accordance with corresponding material codes (SIA 262 to 266)
  - Project specific deflection limits may be agreed upon with the supervisory authority.
    - → Limits can be relaxed for secondary members and special sections (feeder tracks, multiple track lines)
    - → Long span bridges (l > 200 m) require special attention

Limit State	**Consequences of effects of actions**		
	irreversible	reversible	reversible
	Load case		
	occasional	frequent [1]	quasi-permanent
Functionality [2]			
• deflections [3]			
- $v \le 80$ km/h		$w \le l / 800$	
- 80 km/h $\le v \le$ 200 km/h		$w \le l / (15v - 400)$	
• track twist			
- $v \le 120$ km/h		$\alpha_t \le 1.0$ mrad/m	
- 120 km/h < $v \le$ 200 km/h		$\alpha_t \le 0.7$ mrad/m	
- $v > 200$ km/h		$\alpha_t \le 0.3$ mrad/m	
• relative vertical displacement of deck ends behind abutments [5]			
- $v \le 160$ km/h		$\delta_v \le 3$ mm	
- $v > 160$ km/h		$\delta_v \le 2$ mm	
Appearance			$w \le l / 700$ [6] [7]

See notes below

Notes:

1) Deflection due to the variable leading action only shall be considered.
2) For structures with multiple tracks, the functionality shall be verified for up to two simultaneously loaded tracks. The serviceability limits are valid for structures with ballasted track. For structures with slab track, the serviceability limits shall be specified after prior agreement with the supervisory authorities.
3) Deflection due to Load Model 1 or 2, including factors Φ and α. The factor α may be taken as 1.0.
4) Relevant track twist due to:
   – Load Model 1 or 2 including factors Φ and α and associated horizontal forces or
   – Load Model 3 including factor Φ and associated horizontal forces.
5) Relative vertical displacement due to:
   – Load Model 1 or 2 including factors Φ and α.
6) Deflection after deduction of camber, if present. Any long-term effects due to shrinkage, relaxation or creep shall be considered.
7) Deflection due to the actions and long-term effects after installation of the relevant technical equipment.

Conceptual Design

Design Criteria – Structural Safety and Serviceability

Vibrations

Schwingungen

Design Criteria – Structural Safety and Serviceability: Vibrations

- **Vibration limit criteria for**
  Pedestrian and cycle-path bridges:

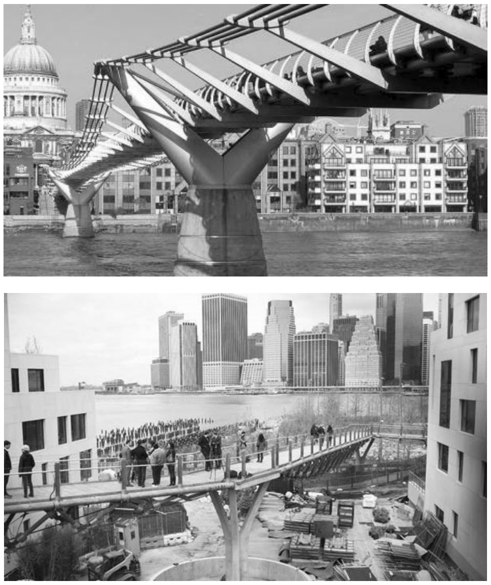
Covered in SIA 260 – Appendix C and 261 Chapter 9

- Control of vibrations to ensure pedestrian comfort is a critical aspect of the design
- Codes provide guidelines in terms of limits on eigenfrequencies.
- Deviations from these limits require explicit modelling of pedestrian movements and dynamic structural response

Limit state	**Eigenfrequency [Hz]**
Comfort	
• vertical vibrations	$f > 4.5$ or $f < 1.6$
• horizontal vibrations (transverse)	$f > 1.3$
• horizontal vibrations (longitudinal)	$f > 2.5$

For comparison:

- Pace frequency for walking ≈ 2.0 Hz
- Pace frequency for running ≈ 2.4…3.5 Hz



Notes:

These comfort requirements also apply to roadway and railway bridges that carry pedestrian traffic.

Note that excessive vibrations could also lead to structural issues in the long term, in the form of distortion induced fatigue of steel members/connections, or simply loss of functional effectiveness.

The explicit modelling of the dynamic structural response is complicated by the fact that the effective damping ratio (which often includes significant contributions from non-structural elements) is difficult to estimate at the design stage. In case of doubt, it may be worthwhile providing space (and funds) for optional vibration reducing measurements such as tuned mass dampers, which are only installed in case that the built structure does experience excessive vibrations.

Further reading:

Sétra: *Footbridges: Assessment of vibration behaviour of footbridges and pedestrian loading*, Technical Guide, October 2006.
fib: *Guidelines for the design of footbridges*, fib bulletin 32, November 2005

Photo Credits:

https://www.weltderphysik.de/gebiet/technik/news/2017/was-die-millennium-bridge-ins-wanken-brachte/
https://www.brooklynpaper.com/bounce-in-our-step-squibb-park-bridge-reopens-after-32-month-closure/

Design Criteria – Structural Safety and Serviceability: Vibrations

- **Vibration limit criteria for**
  (High-speed) railway bridges:

  Covered in EN 1990 A1 & 1991-2:

  - EN 1991-2 §6.4.4 outlines procedure to determine whether a dynamic analysis is required depending on design speed and eigenfrequencies

  Traffic Safety:

  - If a dynamic analysis is required, EN 1990 A1 §A2.4.4.2.1 specifies limits on peak vertical accelerations along the track:
    - 3.5 m/s^2 for ballasted track
    - 5 m/s^2 for direct fastened tracks

    Above limits ensure traffic safety → prevention of track instability (e.g. “Schotterflug”)
  - It is recommended that the first eigenfrequency of lateral vibration of a span is not less than 1.2 Hz

Photo Credit: https://www.interrail.eu/en/plan-your-trip/trains-europe/high-speed-trains

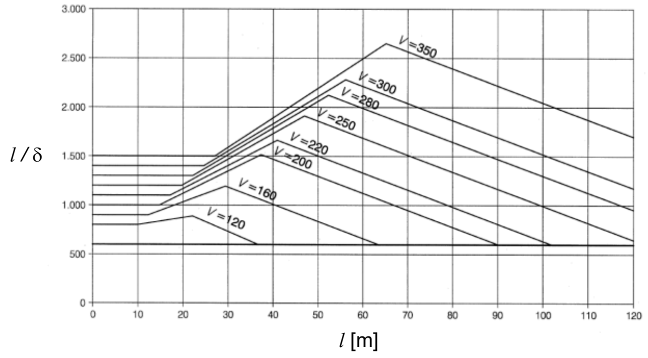
Design Criteria – Structural Safety and Serviceability: Vibrations

- **Vibration limit criteria for (High-speed) railway bridges:**

  Covered in EN 1990 A1 & 1991-2:

  Passenger Comfort:

  - Depends on vertical acceleration inside the coach.
  - Recommended levels of comfort (EN 1990 A1, Table A2.9):
    - Very good → 1.0 m/s²
    - Good → 1.3 m/s²
    - Acceptable → 2.0 m/s²
  - EN 1990 A1, Figure A2.3 provides deflection limits to implicitly ensure very good level of comfort.
  - Alternatively, a dynamic vehicle/bridge interaction analysis may be used to explicitly determine vertical accelerations. This analysis is based on real trains, i.e. not load models.



EN 1990 A1, Figure A2.3

As in pedestrian bridges, the explicit modelling of the dynamic structural response (vehicle/bridge interaction analysis) is complicated by the fact that the effective damping ratio is difficult to estimate at the design stage. However, contributions of non-structural elements are typically smaller in railway bridges. On the other hand, measures to reduce vibrations are much more difficult to provide (higher mass of bridge structure).

Conceptual Design

Design Criteria – Structural Safety and Serviceability

Clearances

Lichtraumprofile

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

From the definition of a bridge:

- A bridge provides a passage for vehicles, people, water, materials, utilities, …
- A bridge crosses a natural or manmade obstacle

Hence, the geometry of the bridge is determined from the geometry of the objects that it provides passage to and the objects that it crosses.

Example: Ohio River Bridge Crossing near Wellsburg, WV, USA (expected opening 2021)

- Bridge typology, span arrangement and erection schemes were dictated by the clearance requirements
- Various types of clearances had to be provided and at different stages:
  - Navigational, Rail, Vehicular, Pedestrian & Cyclist, Trail
  - During construction, service and future change of usage

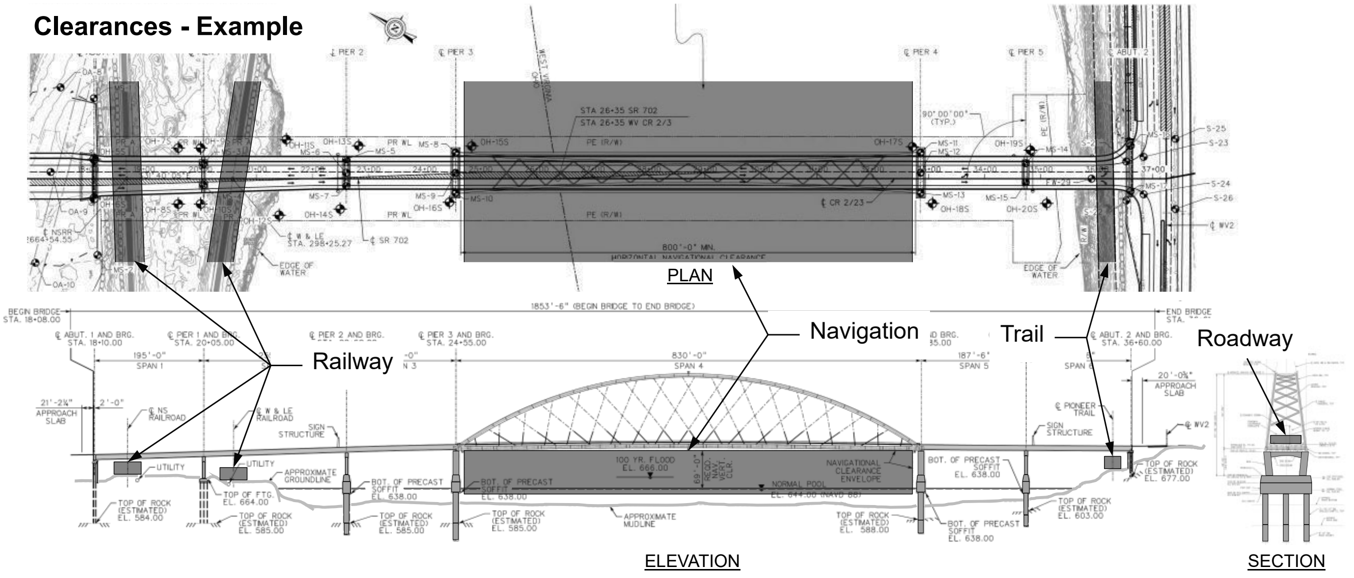
Example:

Ohio River Bridge Crossing near Wellsburg, WV, USA
Owner: West Virginia Department of Highways
Design Team: RS&H, COWI, TRC
Contractor: Flatiron

Photo Credits: Rendering by COWI for Flatiron.

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Example



Example: Ohio River Bridge Crossing near Wellsburg, WV, USA

This Ohio River Crossing connects the cities of Brilliant, OH and Wellsburg, WV with a total length from abutment to abutment of 565 m and is currently under construction with a target completion year of 2021. A combination of clearance requirements had to be considered:

- The main span needed to provide a horizontal navigation clearance of 245 m and vertical navigation clearances of 21 m and 3 m above and below normal pool elevation, respectively. In addition a horizontal navigation clearance of 140 m had to be provided during the construction stage. The horizontal clearance requirements dictated the minimum length of the main span and the erection scheme. In order to minimise the impact on navigation during erection, the arch span will be constructed on temporary falsework along the shore, floated into its final position on barges and lifted onto the piers with jacks. The underwater vertical clearance requirement dictated the foundation type. In order to avoid the use of costly cofferdams and to minimise the main span, a narrow, waterline pile cap was selected, supported on a single row of drilled shafts.
- The North approach spans needed to provide clearance of 15 m (width) by 7 m (height) to two existing railway lines. This requirement dictated the approach span arrangement, girder type (steel) and erection sequence (location of temporary piers and cranes).
- The South approach spans needed to provide clearance of 9 m (width) by 7 m (height) to an existing trail. In addition, the trail alignment, which used to be a railway line, could not be locally diverted because the railway company had reserved the right to re-converted into a railway line. These requirements dictated the location of the South abutment. As a consequence, the last approach span had to include the flared roadway geometry at the T-intersection over the abutment, resulting in a complicated girder and expansion joint layouts.
- The bridge superstructure needed to provide vertical clearance to vehicular traffic of 4.5 m.

It should be noted that multiple entities (US Coast Guard, Railway Companies, Ohio & West Virginia State DOTs, local community groups, local airports) were involved in determining the clearance requirements, while some of the requirements were defined/modified during the bid design phase.

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

During the planning phase:

- Define the use of the bridge
  … road, railway, etc
  … clearance requirements of vehicles on bridge
- Identify obstacles that thee bridge needs to cross
  … over
  … under
- Proactively, reach out to all affected entities
  (some may not be aware of the bridge project):
  … road authorities, railway companies, coast guard, airports, utility companies, etc.
  … establish present and future requirements
- Clearance restrictions of nearby structures may dictate the bridge type and/or erection methods. Consider
  … how the bridge will be constructed
  … how material, equipment and prefabricated elements will be transported to the site

Example:

Replacement of Willis Avenue Bridge, New York, NY (2010).
Designer: Hardesty & Hanover LLP, STV Inc.
Contractor: Kiewit Constructors Inc/Weeks Marine Inc. Joint Venture
Owner: NYCDOT/NYSDOT
Photo Credits: NYCDOT, STV Inc.

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

During the planning phase:

- Define the use of the bridge
  … road, railway, etc
  … clearance requirements of vehicles on bridge
- Identify obstacles that thee bridge needs to cross
  … over
  … under
- Proactively, reach out to all affected entities (some may not be aware of the bridge project):
  … road authorities, railway companies, coast guard, airports, utility companies, etc.
  … establish present and future requirements
- Clearance restrictions of nearby structures may dictate the bridge type and/or erection methods. Consider
  … how the bridge will be constructed
  … how material, equipment and prefabricated elements will be transported to the site

Example 2:

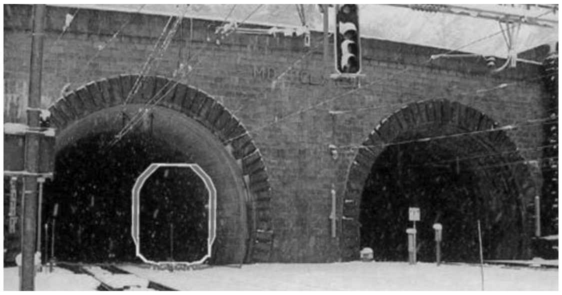
Letzigrabenbrücke, SBB Durchmesserlinie Zürich (2015)
Designer: Bänziger Partner AG
Contractor: ARGE ABD (Strabag / Stutz / Anliker / Kibag / Frutiger)
Owner: SBB
Photo Credit: Stutz AG / Brückenberatung Wopmann GmbH

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

Clearance Profiles are specified in Guidelines published by:

- BAV – Bundesamt für Verkehr
  [Federal Office of Transport]
  Ausführungsbestimmungen zur Eisenbahnverordnung (AB-EBV)
  [Implementing provisions for the Railway Ordinance]
- VSS – Schweizerischer Verband der Strassen- und Verkehrsfachleute
  [Swiss Association of Road and Transportation Professionals]
  Standards 40 201 & 40 202 – Typical Geometric Profiles
- ASTRA - Bundesamt für Strassen
  [Federal Roads Office (FEDRO)]
  Guidelines – 11001 – Typical Profiles – 1st and 2nd Class National Roads with direction separation



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Verkehr BAV

VSS

Forschung und Normierung im Strassen- und Verkehrswesen
Recherche et normalisation en matière de route et de transports
Ricerca e normalizzazione in materia di strade e trasporti
Research and standardization in the field of road and transportation

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Strassen ASTRA

Photo Credit: VÖV UTP - R RTE 20012 – Lichtraumprofil – Normalspur

"With the new edition of the AB-EBV as of 1.11.2020, the R RTE 20012 is invalid. A total revision is being prepared. Leaflets on the new AB-EBV as of 1.11.2020“ (https://www.voev.ch/de/Technik/RTE-Webshop/Start/Detaillierte-Produktedaten?productId=543)

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

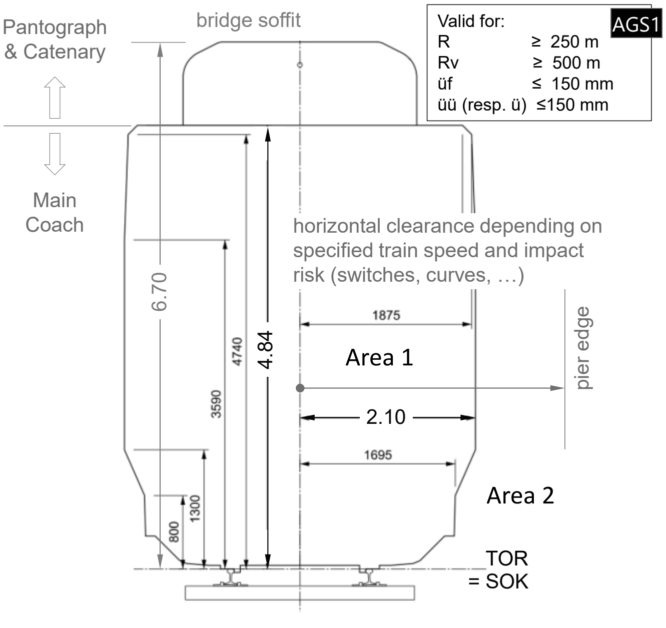
- BAV – Bundesamt für Verkehr
  A-EBV
  [Clearance Profile – Standard Gauge]

  Clearance Profile EBV 4 (Normalspur):
  Applicable for:
  - New lines for the North-South routes Basel-Chiasso and Basel-Iselle
  - New and extension lines with V > 160 km/h

  Note basic dimensions:

Area 1 height	= 4.84 m
Area 1 width	= 4.20 m

  By default, SBB requires a vertical clearance of 6.70 m for new bridges. Lower clearances can often be agreed with SBB (extra cost for catenary adjustments)



Valid for:

R	≥ 250 m
Rv	≥ 500 m
üf	≤ 150 mm
üü (resp. ü)	≤150 mm

Figure Notes:

Area 1: Encroachment from existing system components must be registered. Temporary installations may be permitted up to the limit of the fixed systems.

Area 2: Encroachment subject to approval depending on type.

Figure Legend:

TOR : Top of Rail (in German SOK = SchienenOberKante)
R : Horizontal radius of curvature
Rv : Vertical radius of curvature
ü: Überhöhung. Superelevation is the rate of change in elevation (height) between the two rails or edges.
üf: Überhöhungsfehlbetrag. The superelevation deficiency is the difference between the superelevation that would be necessary to fully compensate for the lateral acceleration at the maximum permitted speed and the actual superelevation of a track curve.
üü: Überhöhungsüberschuss

Horizontal clearances along Swiss railway lines are defined in the AB-EBV (Ausführungsbestimmungen zur Einsenbahnverordnung)

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

- BAV – Bundesamt für Verkehr

  A-EBV

  [Clearance Profile – Standard Gauge]

  Clearance Profile EBV 4 (Normalspur):

  Applicable for:

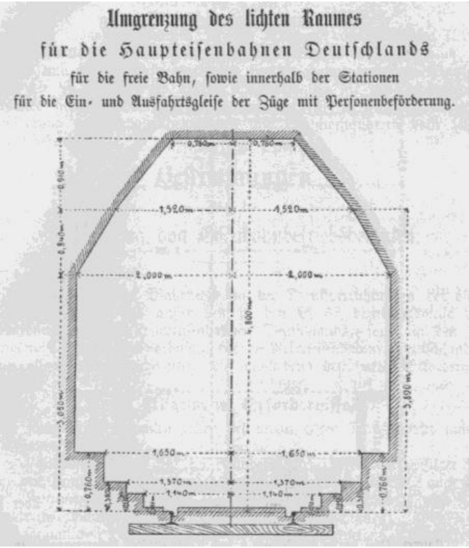
  - New lines for the North-South routes Basel-Chiasso and Basel-Iselle
  - New and extension lines with V > 160 km/h

  Note basic dimensions:

  Area 1 height = 4.84 m
  Area 1 width = 4.20 m
  } Dynamic approach

  Compare to German Regulations (1892 – 1991):

  Envelope height = 4.8 m
  Envelope width = 4.0 m
  } Static approach



Note that the standard track clearance was calculated until 1991 based on a static approach. The modern clearances adopt a dynamic approach, i.e. considering the movement of the trains.

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

- BAV – Bundesamt für Verkehr

  A-EBV

  [Clearance Profile – Standard Gauge]

  Clearance Profile EBV A (Meterspur):

  Applicable for:

  - Adhesion railways and funiculars without transporter wagons or trailers

  Note basic dimensions:

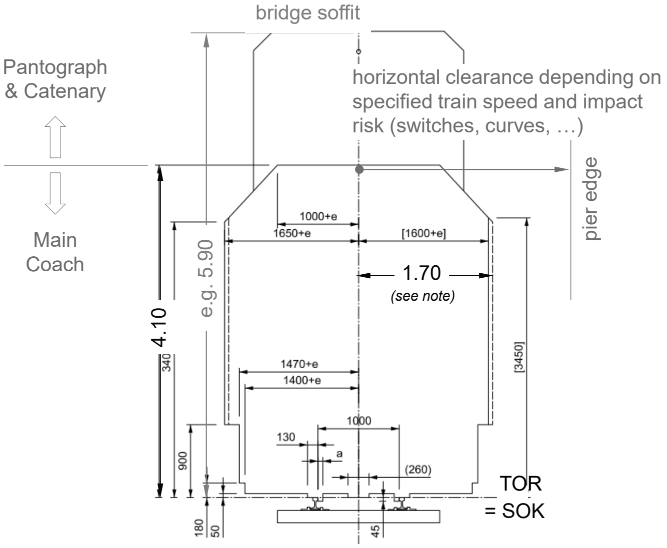
  Envelope height = 4.1 m

  Envelope width = 3.3 m + 2*e*

  where *e* accounts for radius of curvature, *R*

  $e = (25 \text{ m}^2) / R$

  Larger vertical clearances (e.g. 5.90 m RhB) are requested for new bridges. Lower clearances can often be agreed (extra cost for catenary adjustments)



Example: For a radius of curvature of R = 500 m, the curve extension is e = 25 m^2 / 500 m = 50 mm.

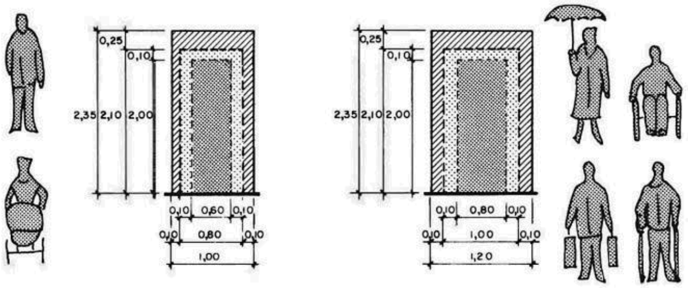
Horizontal clearances along Swiss railway lines are defined in the AB-EBV (Ausführungsbestimmungen zur Einsenbahnverordnung)

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

- VSS – Standards 40 201 & 40 202
  Typical Geometric Profiles

  Clearance Profile for Pedestrians
  - Varies based on the expected amount of pedestrians and the desired comfort level
  - Normal range of motion:
    Horizontal / Vertical = 10 cm
  - Safety margin:
    Horizontal = 10 cm
    Vertical = 25 cm
  - Next to walls, buildings, etc. an additional clear width of 25 cm is required (50 cm for lanes with heavy traffic)



Basic dimensions of users	Width (m)	Height (m)
Pedestrians with or without strollers	0.60	2.00
Pedestrians with luggage, umbrella; wheelchair	0.80	2.00

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

- VSS – Standards 40 201 & 40 202

  Typical Geometric Profiles

  Clearance Profile for Light Two-Wheelers
  - Generally assuming:

    Radius of curvature > 80 m (i.e. straight)

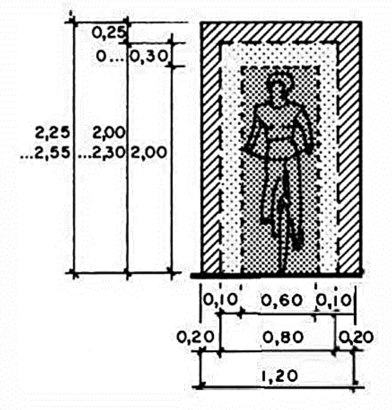
    Grade < 4%
  - Normal range of motion:

    Horizontal = 10 cm (20 – 40 cm if Grade ≥ 4%)

    Vertical = 0 – 30 cm
  - Safety margin:

    Horizontal = 20 cm

    Vertical = 25 cm
  - Next to walls, buildings, etc. an additional clear width of 25 cm is required



Basic dimensions of users	**Width (m)**	**Height (m)**
Light two-wheeler	0.60	2.00

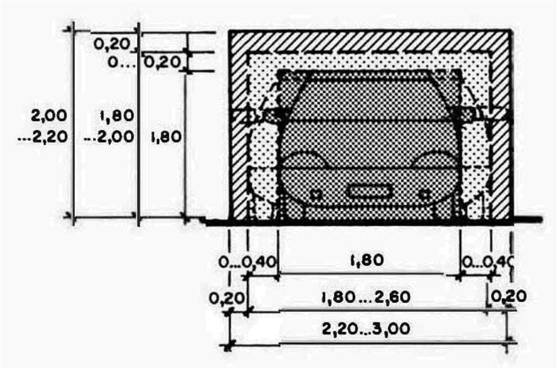
For R > 80 m: When cornering, because of their inclined position, light two-wheelers require a greatly increased range of motion.

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

- VSS – Standards 40 201 & 40 202
  Typical Geometric Profiles

  Clearance Profile for Passenger Cars & Vans
  - The range of motion depends on speed
  - Normal range of motion:
    Horizontal = 0 – 40 cm
    Vertical = 0 – 20 cm
  - Safety margin:
    Horizontal / Vertical = 20 cm
  - Values apply to straight sections
  - In the case of tight curves, additional clearance for the heights is necessary for long vehicles



Basic dimensions of users	Width (m)	Height (m)
Passenger cars	1.80	1.80
Delivery vans, minibuses and mobile homes (< 3.5 t)	2.10 – 2.20	2.70 – 3.00

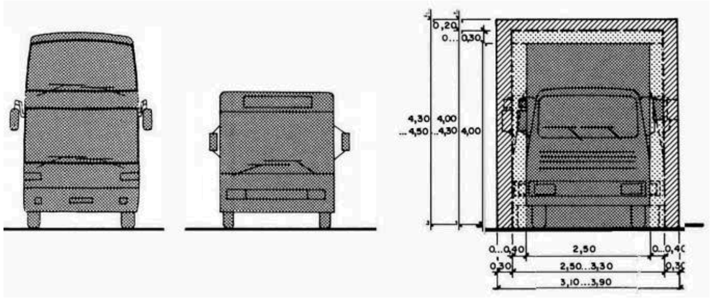
Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

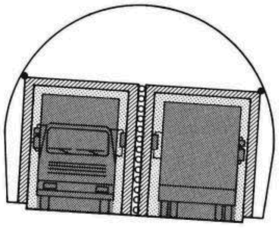
- VSS – Standards 40 201 & 40 202

  Typical Geometric Profiles

  Clearance Profile for Heavy Trucks & Buses
  - The range of motion depends on speed
  - Normal range of motion:
    - Horizontal = 0 – 40 cm
    - Vertical = 0 – 30 cm
  - Safety margin:
    - Horizontal = 30 cm
    - Vertical = 20 cm
  - These values apply to straight sections. In the case of tight curves, additional clearance for the heights is necessary for long vehicles.
  - The cross slope must also be taken into account



Basic dimensions of users	Width (m)	Height (m)
Heavy trucks & buses	2.50	4.00
Agricultural vehicles	2.50 – 3.50	3.00 – 4.00



Design Criteria – Structural Safety and Serviceability: Clearances

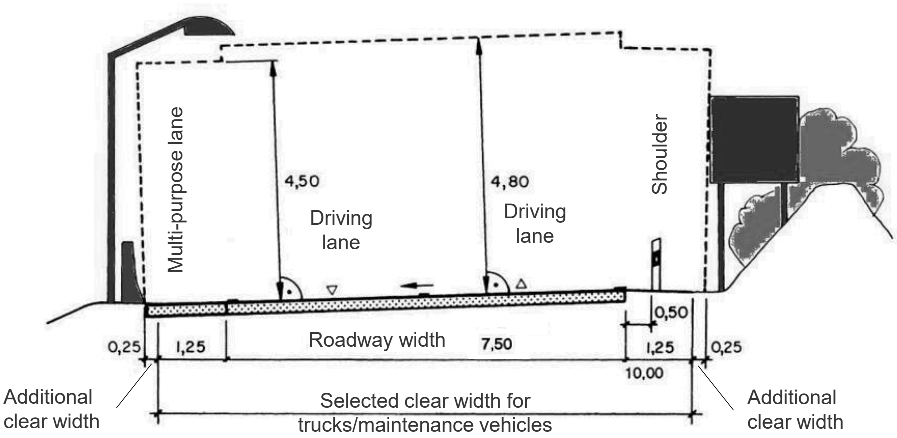
Clearances - Swiss Standards

- VSS – Standards 40 201 & 40 202
  Typical Geometric Profiles

  Clearance Profile Example

Typical geometric profile within water protection areas

Typical geometric profile outside water protection areas



Design Criteria – Structural Safety and Serviceability: Clearances

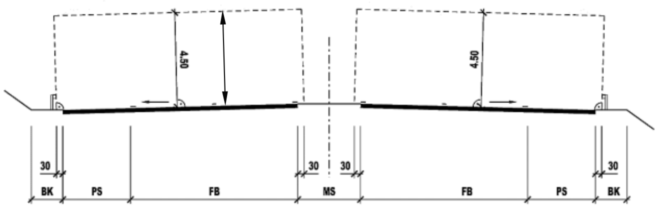
Clearances - Swiss Standards

- ASTRA – Guidelines 11001

  Typical Profiles – 1st and 2nd Class National Roads with direction separation

  Clearance profile requirements (free routes, bridges):
  - width of clearance profile:
    … width required for the vehicles plus
    … movement, overtaking and safety margins
  - side safety margins (0.30 m) extend beyond the edge of the road into the median or the shoulder
  - vertical clearance of 4.50 m:
    … account for cross slope, i.e.
    … measured at right angles to the road surface
    … increase to 4.90 m under traffic sign structures
    … increase by ≥ 0.10 m (min. 4.60 m) under overpasses (deflections, reserve for future strengthening of superstructure / surfacing)

4.50 / 4.60 / 4.90



Design Criteria – Structural Safety and Serviceability: Clearances

Clearances - Swiss Standards

- ASTRA – Guidelines 11001

  Typical Profiles – 1st and 2nd Class National Roads with direction separation

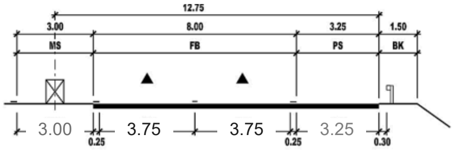
  Lane widths in new motorways (see figures at right):

  - 2 lanes: 3.75 m per lane
  - > 2 lanes: right lane 3.75 m, other lanes 3.50 m
  - emergency lane 3.25 m
  - directional separation 3.00 m

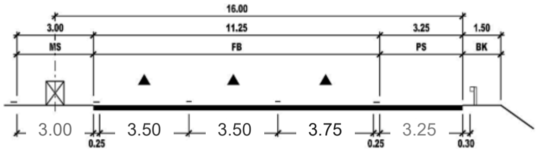
  Minimum lane widths in rehabilitation (not illustrated):

  - 2 lanes: 3.50 m per lane
  - >2 lanes: left lane 3.25 m, other lanes 3.50 m
  - Emergency lane 2.50 m

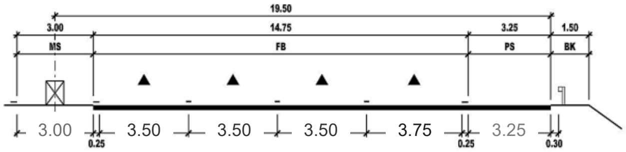
2 lanes / direction



3 lanes / direction



4 lanes / direction



Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

- Reduced (Substandard) Clearances
  - in certain cases, bridge structures do not provide the required standard clearances due to
    … site constraints
    … change of use, and/or standard requirements
  - This should be avoided whenever possible. Even the most high-tech warning measures are typically ineffective in preventing accidents

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

- Reduced (Substandard) Clearances
  - Accidents due to inadequate clearances may result in
    … damage to the structure and/or vehicle
    … personal injury/death
    … bridge/highway closures and traffic discruptions
  - In extreme cases, inadequate clearances may result in collapse of the bridge

Example: I-5 Skagit River Bridge, WA, USA (1955)

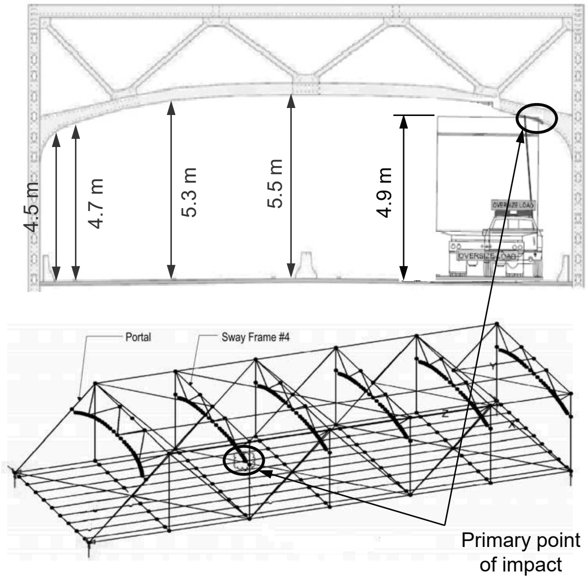
- On May 23, 2013, a span of the bridge carrying Interstate 5 over the Skagit River in the U.S. state of Washington collapsed
- The cause of the catastrophic failure was determined to be an oversize truck striking several of the bridge's overhead sway frames, leading to an immediate collapse of the northernmost span

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

- Reduced (Substandard) Clearances

  Example: I-5 Skagit River Bridge, WA, USA (1955)
  - Variable clearance to sway frames across width.
  - Oversize truck with height of 4.9 m.
  - Pilot car failed to identify clearance issue.
  - Bridge span collapse was initiated when the oversize truck hit Sway Frame 4, causing horizontal deformation of the adjacent vertical member. This deformation pulled the attached upper chord member downward, causing instability in the upper chord.
  - Due to the non-redundant structural system, failure of the upper chord led to collapse of the truss span.



References:

NTSB (National Transportation Safety Board). (2014). “Collapse of the Interstate 5 Skagit River bridge following a strike by an oversize combination vehicle, Mount Vernon, Washington, May 23, 2014.” Accident Rep. NTSB/HAR-14/01, Washington, DC.
https://www.ntsb.gov/investigations/AccidentReports/Reports/HAR1401.pdf

T.D. Stark, R. Benekohal, L.A. Fahnestock, J.M. LaFave, J. He and C. Wittenkeller (2016). I-5 Skagit River Bridge Collapse Review, Journal of Performance of Constructed Facilities, Vol. 30, Issue 6 (December 2016)
DOI: 10.1061/(ASCE)CF.1943- 5509.0000913

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

- Reduced (Substandard) Clearances

  Other Examples of Oversize Combination Vehicles:

KW1
KW2

Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

- Reduced (Substandard) Clearances
  Local Examples of Oversize Combination Vehicles:

Video source: https://www.tagesanzeiger.ch/panorama/vermischtes/Baggerunfall-auf-A-1-Fahrer-muss-Busse-zahlen/story/16232224

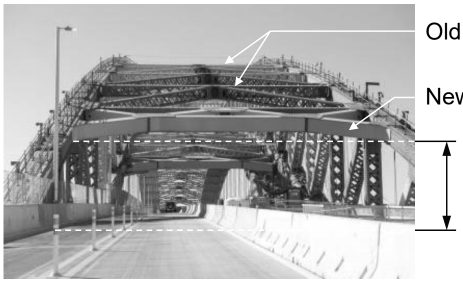
Design Criteria – Structural Safety and Serviceability: Clearances

Clearances

- Change in clearance requirements

  Over the service life of a bridge the clearance requirements may change (usually increase).

  Example: Bayonne Bridge, NY & NJ, USA (1931)



Roadway was raised by 20 m to accommodate post-Panamax ships (2013-2019).

Example:

Bayonne Bridge, Bayonne, New Jersey with Staten Island, New York City, USA
It was the longest steel arch bridge in the world at the time of its completion.
Owner: Port Authority of New York and New Jersey
Designer: Othmar Ammann
Contractor: American Bridge Company

Raising of deck (2013-2019):
Owner: Port Authority of New York and New Jersey
Designer: HDR/WSP (JV)
Contractor: Skanska Koch, Inc. / Kiewit Infrastructure Co. (JV)

Designers took advantage of the structural system of the main span, where the deck is suspended/supported by the arch through vertical hangers/columns. Thus, raising the deck did not alter the basic function of the arch span. On the other hand, the approach spans had to be completely replaced.

Photo Credits:
Elevation View: https://revitalization.org/article/renovation-of-historic-1931-bayonne-bridge-boosts-economy-allows-more-efficient-ships-wins-sustainable-infrastructure-award/
Cross-Section:
https://www.nj.com/hudson/2017/02/bayonne_bridge_opens_to_drivers_but_construction_f.html

Conceptual Design

Design Criteria – Durability
Entwurfskriterien – Dauerhaftigkeit

Design Criteria – Durability

General aspects

Durability is essential and needs to be accounted for from the conceptual design stage to the end of construction. Specific aspects (relevant for all construction materials):

- Avoid joints (→ support and articulation)
- Protect structure from chloride attack
  … reliable waterproofing and controlled drainage of decks
  … minimise exposed surfaces
- Use proper materials, for example
  … avoid weathering steel or timber in wet zones
  … use freeze-thaw resistant concrete
- Carefully detail the entire structure, for example
  ... avoid horizontal surfaces (puddles, “stehendes Wasser”)
  … provide gutters («Tropfkanten»)
- Facilitate access for inspection and maintenance e.g. to:
  … interior of box-girders (h ≥ 1.50 m)
  … expansion joints and bearings (maintenance chamber)
- Ensure quality during execution – the proper execution of a detail is at least as important as choosing the right detail

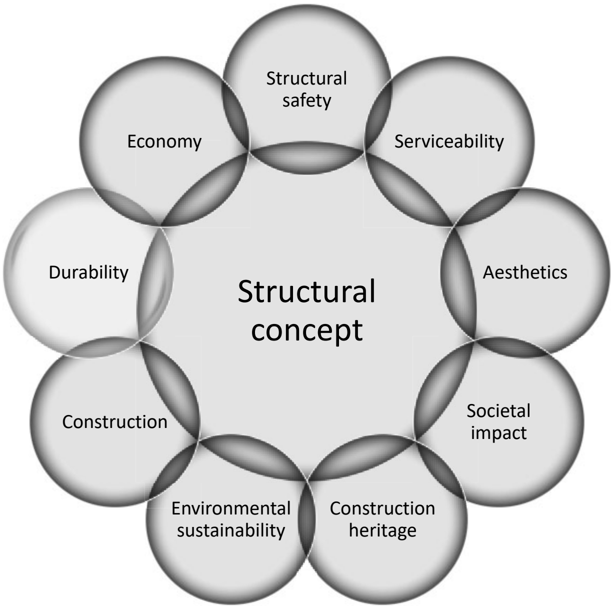


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Photo: Gardiner Expressway, Toronto (taken by kfm)

Photo (animated): Fuengirola footbridge, corroding stay-cable anchorage (taken by kfm)

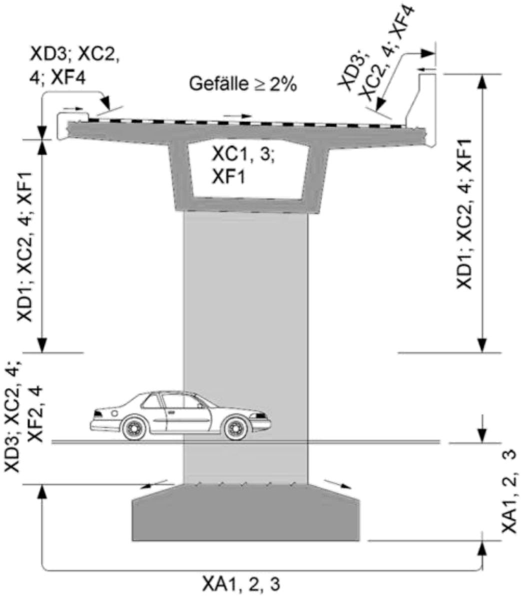
Design Criteria – Durability

Concrete

- Specify concrete with adequate freeze-thaw resistance depending on exposure classes XF (see figure)
- Ensure dense cover concrete (air permeability)
- Make sure that post-tensioning ducts are properly grouted
- Full prestressing (avoid cracks) at least for permanent load
- Specify adequate concrete cover, depending on exposure classes XC, XD and XA (see table and figure) for lifespan of 80… 100 years:

Exposure classes / clear cover (ASTRA RL 12001)		reinforcement cover [mm]	prestressing cover [mm]
XC: Carbonation	XC1-4	40	50
XD: Chloride attack	XD1	40	50
	XD2,3	55	65
XA: Chemical attack (Astra: incl. chlorides)	XA1,2	55	65
	XA3	70	80

(*) increase by 10 mm if concrete permeability is high for XC3,4 and XD



The concrete covers specified in current codes (as shown in the table) are based on experience. Using these “deemed to satisfy” values, it is generally assumed that a lifespan of 80-100 years can be achieved. Future codes (SIA, EC) will probably be performance-oriented, using so-called exposure resistance classes.

Similar as in steel structures, “stainless steel” (reinforcement with high corrosion resistance) is used in exceptional cases only, due to the much higher initial cost. In some countries (US, Canada), epoxy coated reinforcing bars are used in bridge decks. The coating protects the reinforcement from corrosion (and reduces bond, which is however of minor importance) as long as the coating is not damaged. Local defects in the coating may however cause severe local corrosion; in Switzerland, the use of epoxy coated reinforcing bars (brand name “Optimar”) was prohibited based on few such observations after few years of use (1990s). In the light of several decades of positive experience in other countries, this might be worth reconsidering.

Illustration: ASTRA Richtlinie 12001: Projektierung und Ausführung von Kunstbauten der Nationalstrassen, Anhang 6: Anforderungen an Bauwerksteile aus Beton

Design Criteria – Durability

Steel (conventional)

- Ensure proper surface preparation (Sa 2½ or Sa3, edges)
- Apply coating in workshop (quality control, climate)
- Ensure air-tightness of inaccessible elements (inside box girders and closed profiles) or provide dehumidification
- Protective coating with adequate protection (category of corrosiveness, usually C3/C4 for bridges)
  … conventional, see table
  … thermal spray zinc coating («Spritzverzinkung»)
  (instead of primer, intermediate + top coating as above)

Typical protective coating for CH steel bridges (SBB AQV 2007, category C4)		thickness [μm]
Primer (*) (base layer)	Two pack zinc epoxy / phosphate (2-K-Epoxidharz-Zinkstaub)	70
Intermediate coatings (2)	Two pack Epoxy MIO (**) (2-K-Epoxidharz-Eisenglimmer)	80
		80
Top coating	Two pack Polyurethane MIO (**) (2-K-Polyurethan-Eisenglimmer)	80

(**) micaceous iron oxide (Eisenglimmer)

MIO (Micaceous Iron Oxide) paints contain iron oxide flakes that create a fish scale (Schuppen) type barrier that protects the steel from water ingress and the coating from UV light degradation.

Reference: SBB Ausführungs- und Qualitätsvorschriften (AQV) für Korrosionsschutz von Stahlbrücken, 2017

Photo: Puende de Hierro Railway bridge across the Guadiana river, Mérida, Spain (William Finch / Eduardo Peralta, 1883, L = 11x55 = 605 m). Taken by kfm.

Design Criteria – Durability

Steel (with improved corrosion resistance)

- Weathering steel («Cortenstahl») may be used without protective coating in many cases / exposures since a protective patina will form if wet/dry phases alternate
- Weathering steel should not be used:
  … in humid sites (< 3 m above river, < 0.5 m above ground)
  … in case of chloride exposure (e.g. crossing a road with de-icing salt deployment, or site close to sea)
- Careful detailing is important for durability and appearance (avoid rust stains)
- Stainless steel is only used in exceptional cases due to the high initial cost

Reference: Thomas Lang, Jean-Paul Lebet: Brücken aus wetterfestem Stahl, tec21, 2002.

Photo: Puente del Milenario sobre el Ebro en Tortosa, J. Martínez Calzón, MC2 Ingeniería. 1982 (one of the first major bridges using weathering steel, main span 180 m).

Design Criteria – Durability

Timber

- Durability is problematic since bridges cannot be completely protected from weathering and humidity
- Improvement by impregnation with chromated copper arsenate (CCA) or oil-tar creosotes (“carbolineum”), but severe environmental issues (prohibited in many countries)
- Careful detailing is important for durability and appearance (protect from weathering, avoid mould, use durable wood where available, see lower example)

The use of CCA (chromated copper arsenate) and similar wood impregnation products like oil-tar creosotes (“carbolineum”) is generally prohibited in most countries, but allowed for selected applications due to lacking alternatives. In Switzerland, they may be used for impregnating railway sleepers and avalanche protection components; in Scandinavian countries the use of CCA in bridges is permitted. The main issue of CCA-impregnated timber is its decommissioning (toxicants particularly from arsenic).

Photo:

Photo top: Flisa bridge, Norway, 2003. Norconsult, https://mapio.net/wiki/Q279109-de/

(full timber bridge, exposed elements protected by copper plates)

Photo bottom: Pyrmont bridge, Sydney, Australia, 1902. Percy Allan. Fourteen ironbark timber Allan truss and approach spans with central steel truss swing spans. Closed to traffic in 1981, monorail use 1988-2013, pedestrian use since 2016.

(Allan trusses are similar to Howe trusses: timber compression diagonals and iron or steel vertical posts. Allan optimised them by splitting the chords in two parallel elements, easing anchorage of the posts, and splicing the chords longitudinally, enabling the use of shorter elements and their replacement).

Design Criteria – Durability

Stay cables

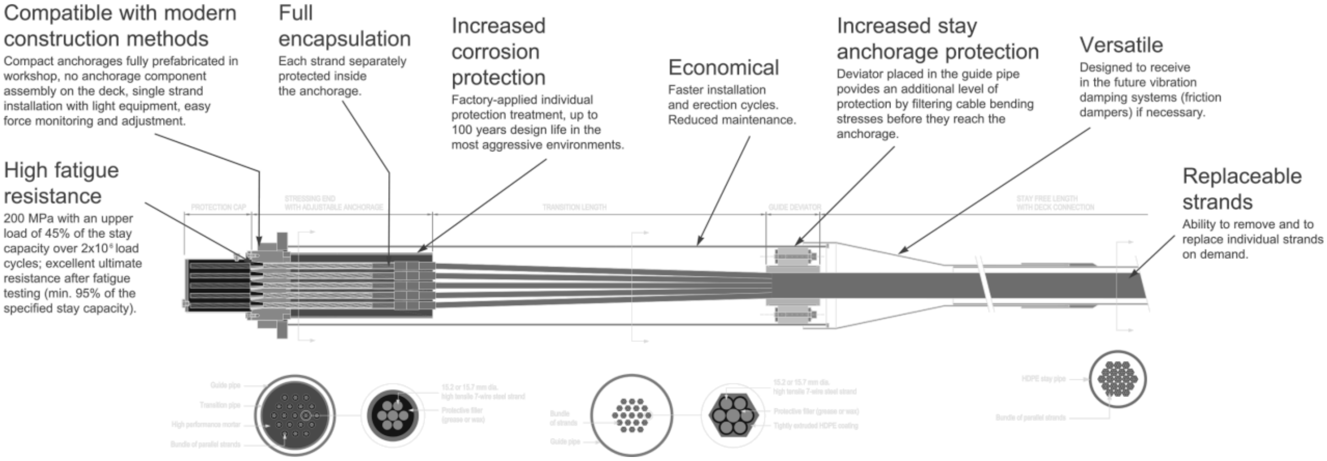
- Require particular attention since they are usually
  … important load-bearing elements
  … subjected to severe exposure

- Stays of early cable stayed bridges had limited durability

- Modern stay cables are high-tech, durable components (see image on next slide):
  … individually encapsulated (sheathed) strands
  … galvanised or epoxy-coated strands
  … replaceable strands and cables (under traffic)
  … dehumidification of ducts
  (in harsh exposure, e.g. marine environment)

Photo: Sondage an Schrägkabel der PüF Oberwies (dsp Ingenieure + Planer AG)

Design Criteria – Durability



Compatible with modern construction methods
Compact anchorages fully prefabricated in workshop, no anchorage component assembly on the deck, single strand installation with light equipment, easy force monitoring and adjustment.

Full encapsulation
Each strand separately protected inside the anchorage.

Increased corrosion protection
Factory-applied individual protection treatment, up to 100 years design life in the most aggressive environments.

Economical
Faster installation and erection cycles. Reduced maintenance.

Increased stay anchorage protection
Deviator placed in the guide pipe povides an additional level of protection by filtering cable bending stresses before they reach the anchorage.

Versatile
Designed to receive in the future vibration damping systems (friction dampers) if necessary.

High fatigue resistance
200 MPa with an upper load of 45% of the stay capacity over 2x10^6 load cycles; excellent ultimate resistance after fatigue testing (min. 95% of the specified stay capacity).

Replaceable strands
Ability to remove and to replace individual strands on demand.

Image: VSL Stay cable system SSI 2000

Conceptual Design

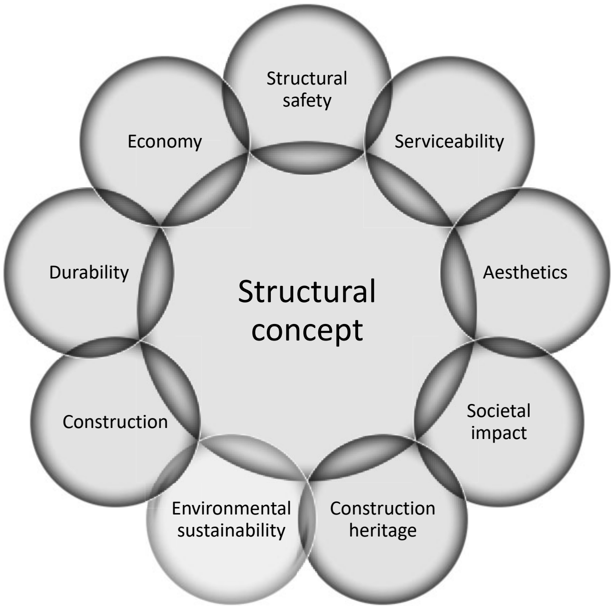
Design Criteria –Environmental sustainability
Entwurfskriterien – Ökologische Nachhaltigkeit

Design Criteria – Environmental sustainability

General aspects

- Environmental sustainability is a decisive design criterion
- Ensure respect of environmental legislation by accounting for related aspects in early design stages
- Longer bridges than strictly necessary may be required to
  … avoid nature reserves and habitats of protected species
  … protect ecologically important river banks and ensure connectivity along these (and along other obstacles)
- Longer river spans may be economical if no temporary dams facilitating access for the construction of river piers and their foundations are prohibited
- Birds are another important criterion, as they
  … use rivers (obstacles crossed by bridges) as routes
  … are attracted by bright lights on bridges
  … hit thin elements of the bridge structure in poor weather

→ Cable-supported structures require special measures or are even prevented near important bird habitats



Design Criteria – Environmental sustainability

Environmental impact of construction

- Negative environmental impact must also be minimised during construction
  - … building piers and foundations from water rather than temporary dam (see previous slide)
  - … avoid spawning season of fish and frogs
  - … avoid periods where flood events are expected

Compensation measures

- Ecological compensation measures are often provided in order to mitigate negative environmental impacts, e.g.
  - … renaturation of built-up banks
  - … planting of native vegetation
  - … providing nesting aids (for birds or bats)
  - … building support structures for fish and frog spawn

Link to economy and structural efficienycy

- Minimisation of material use and emissions are important for environmental sustainability as well as for economy. They are best achieved by structural efficiency.

Photos:

Top: Steinbachviadukt, Sihlsee (2012) © dsp Ingenieure + Planer AG. Bridge built entirely from water using pontoons, providing spawn support structures near the abutment on the side of a nationally protected habitat.

Bottom: nesting aids on a bridge © Tiefbauamt Stadt Zürich

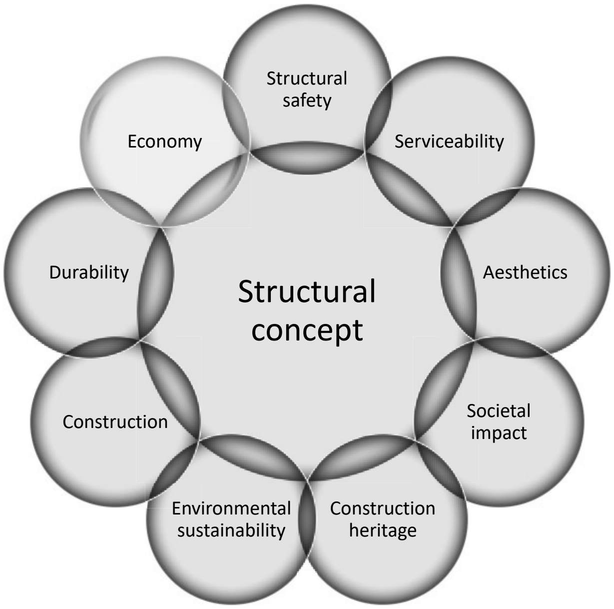
Conceptual Design

Design Criteria – Economy
Entwurfskriterien – Wirtschaftlichkeit

Design Criteria – Economy vs Environmental sustainability

Link between economy and environmental sustainability

- Environmental protection measures are often seen as a cost driver by construction industry
- While this partly applies, economy and environmental sustainability are also related: structurally efficient bridges minimise material use hence cost and emissions
- Unfortunately, the link is loose today since construction materials are too cheap, to the point where wasting material to reduce labour has become usual
- Hopefully, the current trend towards reducing material consumption and greenhouse gas emissions will reinforce the dependency of economy on structural efficiency, and hence, the connection between economy and environmental sustainability as well.



While environmental protection measures are primarily seen as a cost driver by the construction industry – which is partly true – economy and environmental sustainability are effectively also related and need not be contradictory: Both criteria benefit from the minimisation of material use, which can best be achieved by maximising structural efficiency particularly in bridges, where the structure makes up for most of the material consumption.

Unfortunately, however, as already discussed in the context of aesthetics as a design criterion (Sub-Chapter Aesthetics), structurally efficiency and economy have been disconnected by the diverging development of material and labour cost over the last decades, with construction materials becoming so cheap that wasting material to save labour has become common practice.

Hopefully, the current trend towards reducing material consumption and greenhouse gas emissions will reinforce the currently rather loose link between economy and structural efficiency, and hence the connection between economy and environmental sustainability in terms of emissions and material use as well.

Design Criteria – Economy

General aspects of economy in bridge design

- Economy is even more relevant in bridge design than forbuilding structures, since

→ bridges are usually public works, paid by tax money

→ in bridges, the structure makes up for most of the total cost (whereas in buildings they are a smaller part)

- Though clients are aware that life-cycle costs are relevant, decisions are regularly taken based on initial cost (particularly in design-build competitions)
- In order to achieve an economic (and eco-friendly) solution:
  … account for construction method in early design stage
  … use economic, durable materials (depending on site)
  … save materials by maximising structural efficiency
  … simplify geometry and seek repetitiveness

Photos

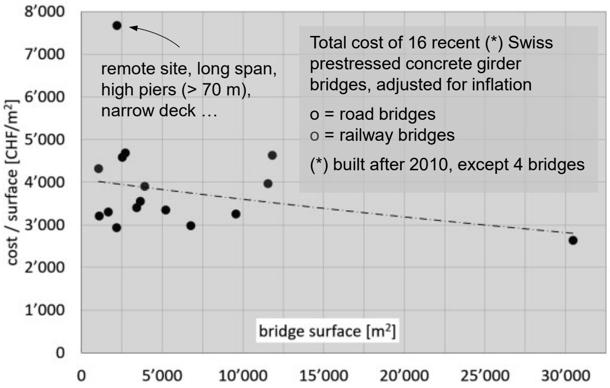
Top: Pabellón Puente (2008), Zaha Hadid Architects © Periódico de Aragón. Since the construction process was neglected in the design, erection was extremely complex (a masterpiece of construction engineering by FHECOR, yet no masterpiece of bridge design). Note also the provisional dam causing negative environmental impact on riverbed and bank.

Bottom: Formwork of Kettenbrücke in Aarau (2022) © Aargauer Zeitung. Excessive cost and waste caused by a design using by free forms, requiring furniture-type formwork that could only be used one single time.

Design Criteria – Economy

Cost estimates

- Cost estimates are essential to clients (particularly in political decision processes)
- When comparing costs, make sure to compare equivalent costs, i.e., cost with or without:
  … client/owner overhead, design fees
  … bridge equipment (surfacing, drainage, …)
  … percentages for unforeseen, VAT
- Rough estimates are possible based on the cost per bridge surface (e.g. ca. 3’500 CHF/m^2 total cost for Swiss road bridges, top figure) if reference objects with similar conditions are available regarding
  … location (cost varies strongly even among EU countries)
  … construction constraints (under traffic / over railway / …)
- Cost estimates per m^2 may be completely misleading e.g. in footbridges (recent *fib* bulletin 2’000…25’000 CHF/m^2)
- Better estimates are hardly possible by considering the share of individual components to the cost (bottom figure)



remote site, long span, high piers (> 70 m), narrow deck …

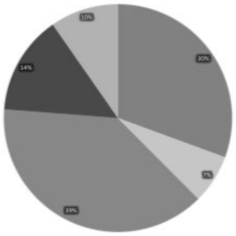
Total cost of 16 recent (*) Swiss prestressed concrete girder bridges, adjusted for inflation

o = road bridges
o = railway bridges

(*) built after 2010, except 4 bridges

Contribution to total cost for 6 Swiss prestressed concrete girder bridges (commissioned after 2010)

Site installations, various
Scaffolds
Concrete works (concrete, formwork, reinforcement, prestressing)
Earth works, excavation pits, piles
Waterproofing, surfacing, drainage



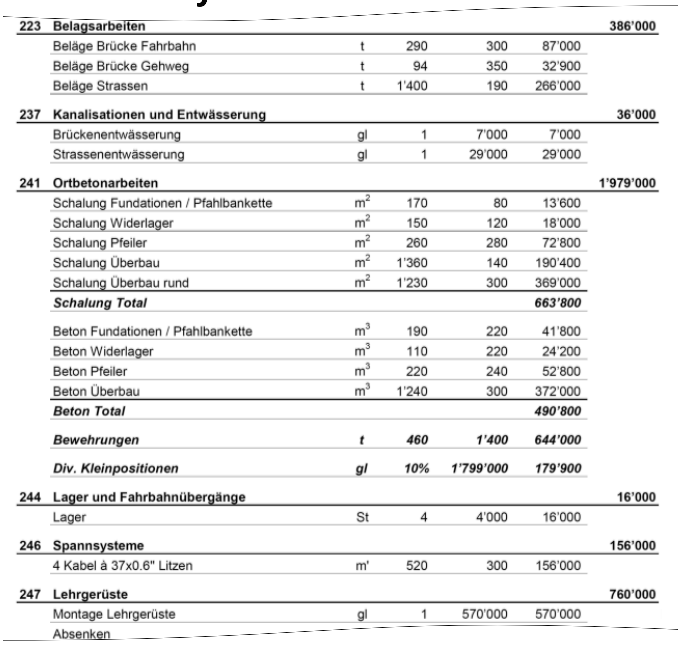
Graphs:

Adapted (inflation, layout) from O. Tepasse, I. Röthlisberger, “Kostenentwicklung in heutigen Brückenbauprojekten – Nachrechnung und Verifikation”, Bachelor thesis, 2019.

Design Criteria – Economy

Cost estimates

- More reliable cost estimates are possible once the project is defined such that the main quantities can be determined and the costs evaluated by applying unit prices based on local experience.
- The figure shows an example used in design competitions in CH, following NPK AGS1 ("Normpositionenkatalog" / standardised position catalogue) main positions and quantities)
- Contractor bids may differ significantly from cost estimates not only due to uncertainty of the estimate, but also due to the current construction market (contractor in need for work or not)



223	**Belagsarbeiten**					**386'000**
	Beläge Brücke Fahrbahn	t	290	300	87'000	
	Beläge Brücke Gehweg	t	94	350	32'900	
	Beläge Strassen	t	1'400	190	266'000	
237	**Kanalisationen und Entwässerung**					**36'000**
	Brückenentwässerung	gl	1	7'000	7'000	
	Strassenentwässerung	gl	1	29'000	29'000	
241	**Ortbetonarbeiten**					**1'979'000**
	Schalung Fundationen / Pfahlbankette	m^2	170	80	13'600	
	Schalung Widerlager	m^2	150	120	18'000	
	Schalung Pfeiler	m^2	260	280	72'800	
	Schalung Überbau	m^2	1'360	140	190'400	
	Schalung Überbau rund	m^2	1'230	300	369'000	
	Schalung Total				***663'800***	
	Beton Fundationen / Pfahlbankette	m^3	190	220	41'800	
	Beton Widerlager	m^3	110	220	24'200	
	Beton Pfeiler	m^3	220	240	52'800	
	Beton Überbau	m^3	1'240	300	372'000	
	Beton Total				***490'800***	
	Bewehrungen	***t***	***460***	***1'400***	***644'000***	
	Div. Kleinpositionen	***gl***	***10%***	***1'799'000***	***179'900***	
244	**Lager und Fahrbahnübergänge**					**16'000**
	Lager	St	4	4'000	16'000	
246	**Spannsysteme**					**156'000**
	4 Kabel à 37x0.6" Litzen	m'	520	300	156'000	
247	**Lehrgerüste**					**760'000**
	Montage Lehrgerüste	gl	1	570'000	570'000	
	Absenken					

Conceptual Design

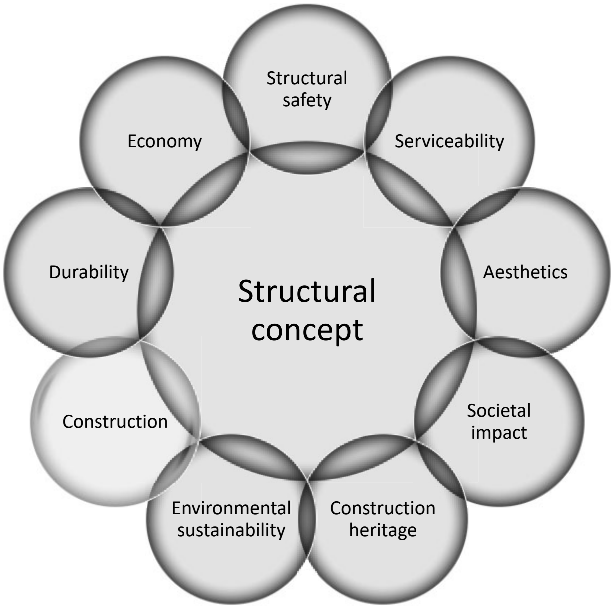
Design Criteria – Construction
Entwurfskriterien – Bauvorgang

Design Criteria – Construction

General aspects

Construction includes:

- Erection method (most relevant aspect)
  - → casting on falsework (conventional scaffolding)
  - → lifting
  - → balanced cantilevering
  - → incremental launching
  - → Movable Scaffold System (MSS)
  - → …
- Type of production
  - → casting in-situ
  - → prefabrication (precast elements)
- Transport of materials or elements of the structure
- New technologies
- …



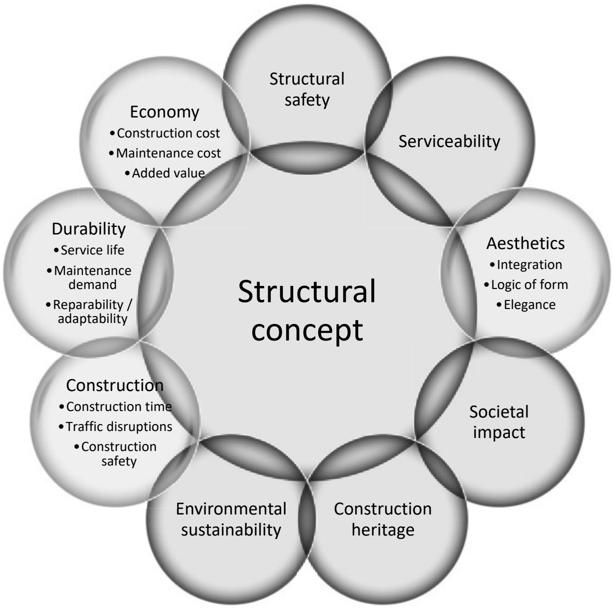
Construction includes not only the erection method, but also other aspects of construction, such as the general type of production (*in-situ* or precast in factory), the transport of materials or elements of the structure, the use of new technologies, etc., which must be taken into account in the conceptual design. However, the erection method is the most relevant aspect and involves many of the other aspects mentioned.

Design Criteria – Construction

General aspects

Choice of the erection method

- The erection method is selected in an iterative process in order to conceive a structure that optimises the given constraints
- Efficient construction is only one of many criteria, but affects many others (see figure)
- The main factors in the iterative process are:
  - → materials
  - → typology of the bridge
  - → topography
  - → cost
- The erection method may significantly influence the dimensioning of the structure



Design Criteria – Construction

General aspects

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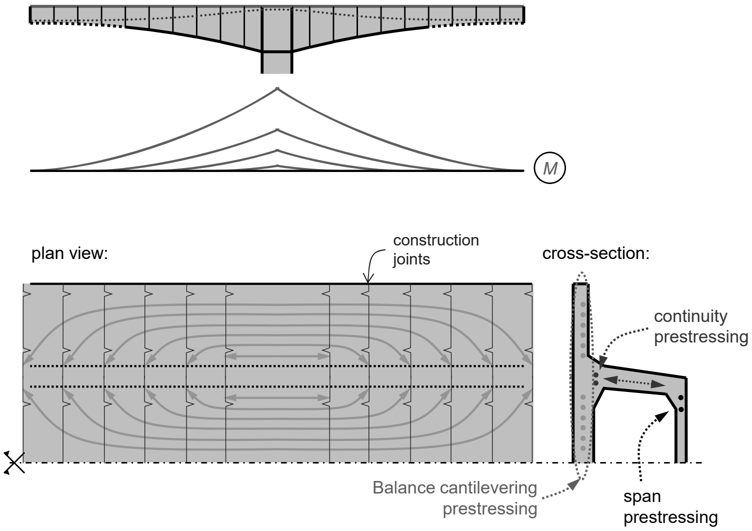

Design Criteria – Construction

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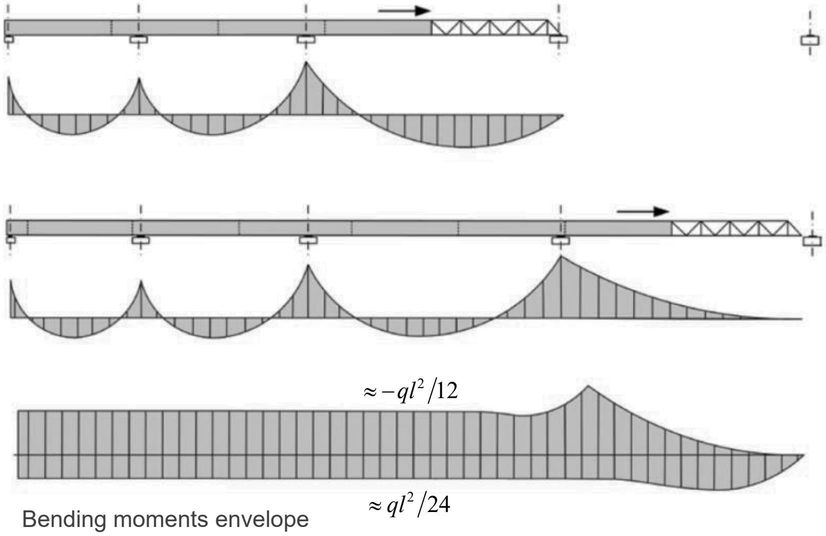
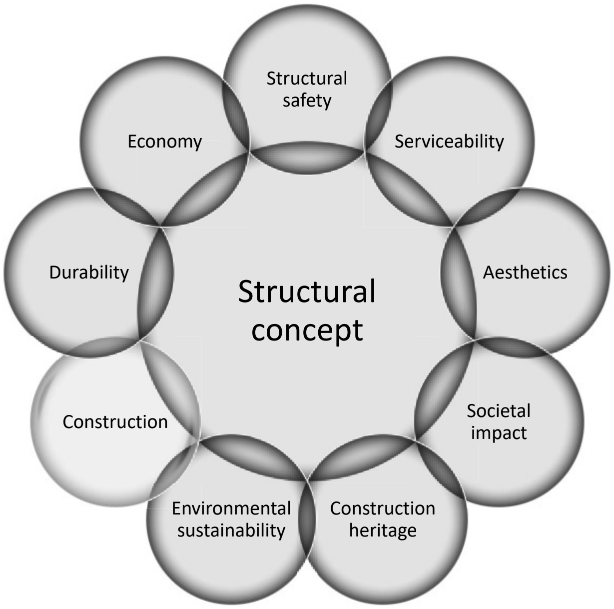


Illustration adapted from Reis Oliveiras, Bridge Design.

Design Criteria – Construction

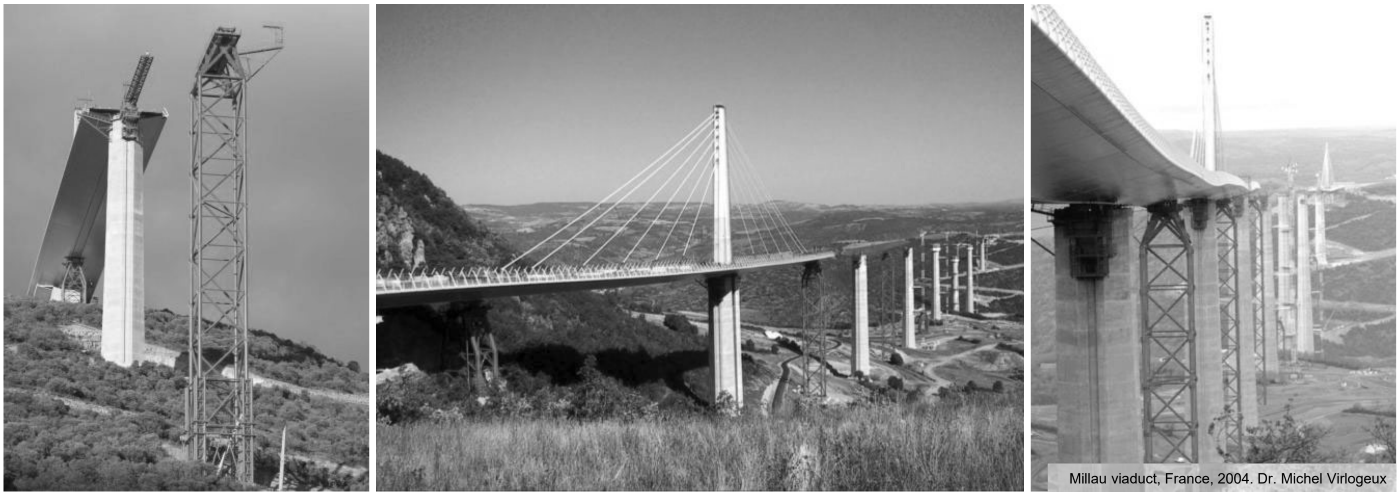
Conclusions:

- The construction process is an integral part of the structural concept
- Neglecting the construction process in the early design phase may lead to excessive cost



Design Criteria – Construction

In extraordinary bridges, the construction process is absolutely key…



Millau viaduct, France, 2004. Dr. Michel Virlogeux

Photos: https://www.constructionequipmentguide.com/

Design Criteria – Construction

In extraordinary bridges, the construction process is absolutely key…

Tamina bridge, Switzerland, 2017. Leonhardt, Andrä und Partner

Photos: Meichtry & Widmer

Design Criteria – Construction

Sometimes … conventional methods are still the only viable solution

Shell Pedestrian bridge over Manzares river, Spain, 2010. Fhecor Ingenieros

Photos: Fhecor Ingenieros

Conceptual Design

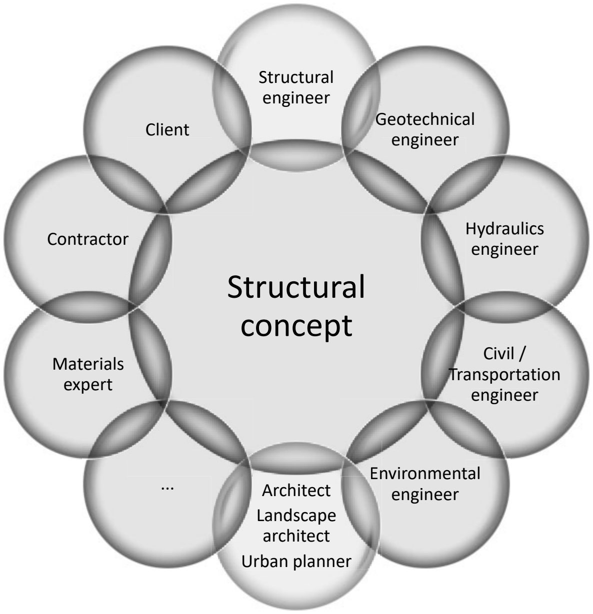
Holistic Design – Process

Ganzheitlicher Entwurf – Prozess

Holistic Design – Process

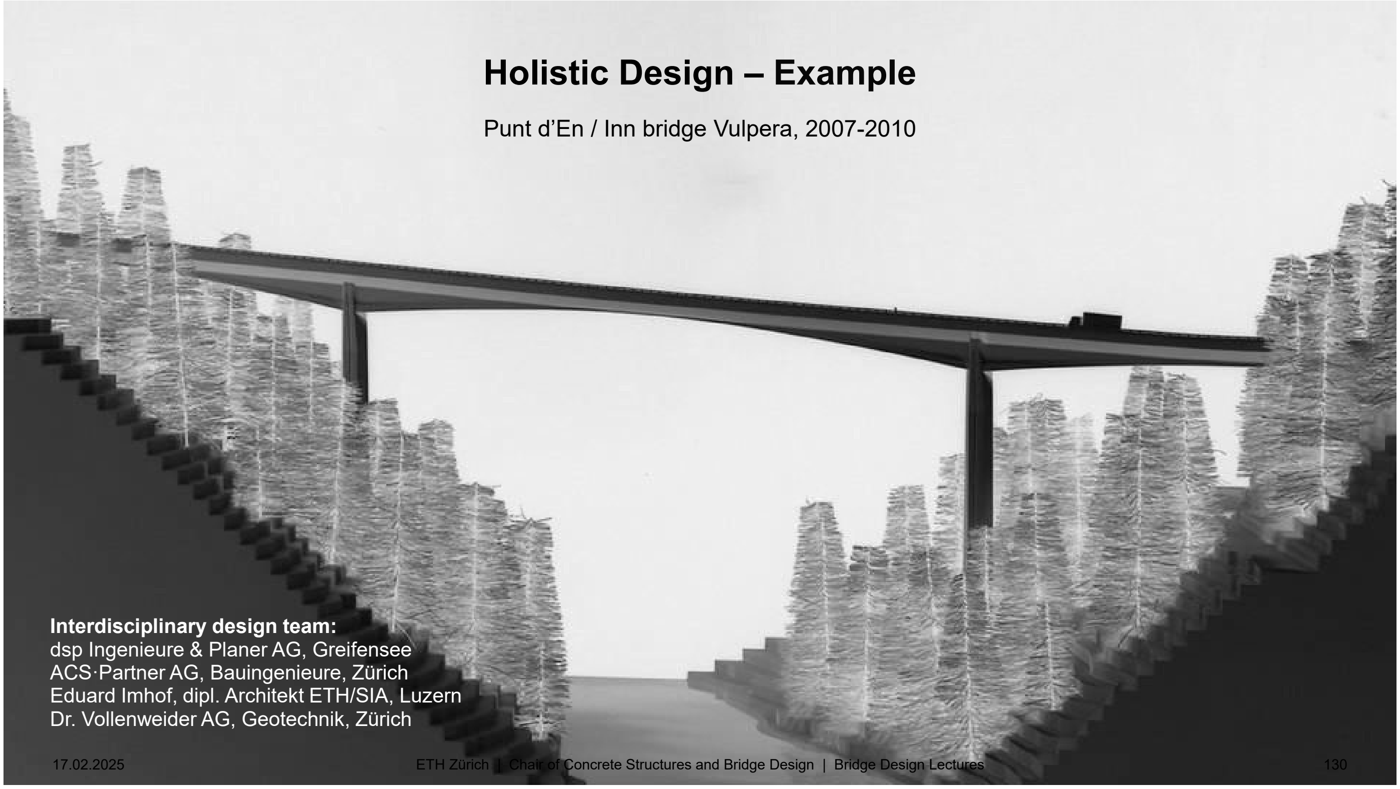
Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓
Design approach / potential solution
↓
Structural concept
↓
Detailing



Holistic Design – Example

Punt d'En / Inn bridge Vulpera, 2007-2010



Interdisciplinary design team:
dsp Ingenieure & Planer AG, Greifensee
ACS·Partner AG, Bauingenieure, Zürich
Eduard Imhof, dipl. Architekt ETH/SIA, Luzern
Dr. Vollenweider AG, Geotechnik, Zürich

Holistic Design – Example

Interdisciplinary design team

Starting point / service criteria
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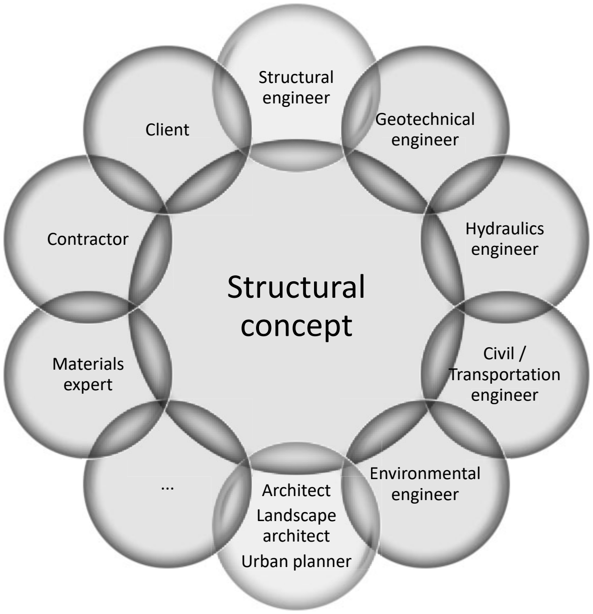
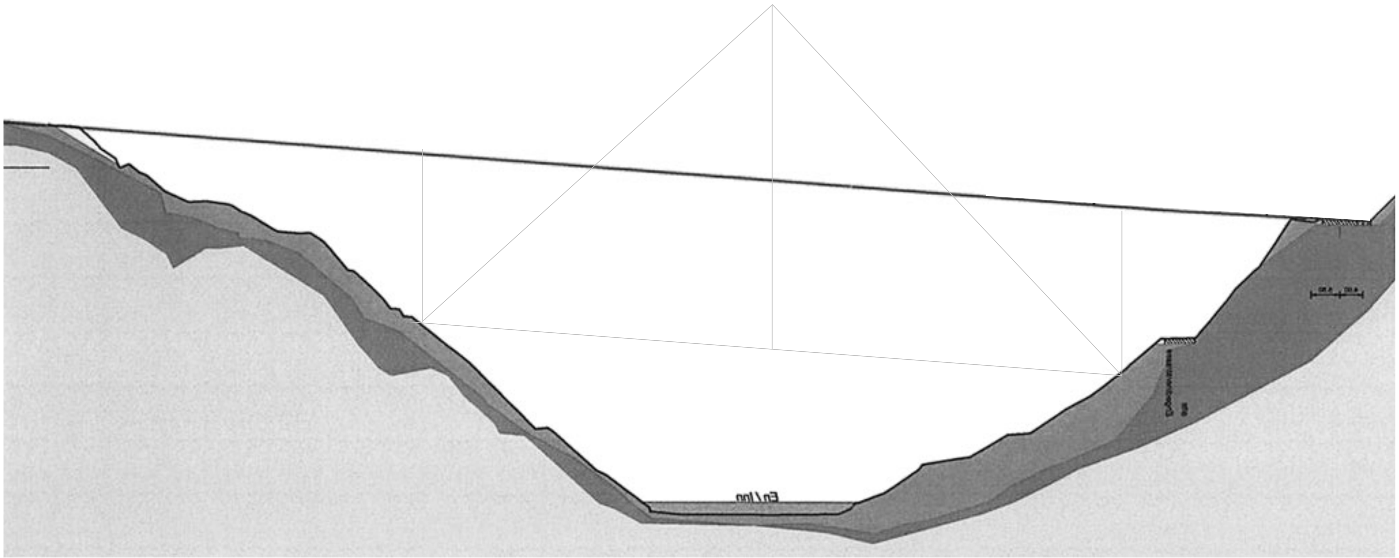
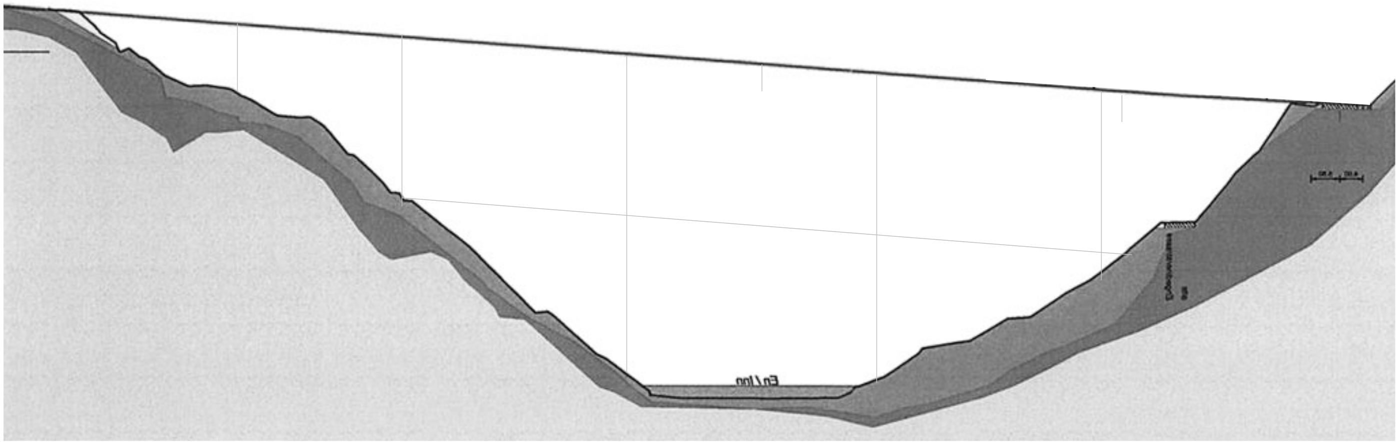


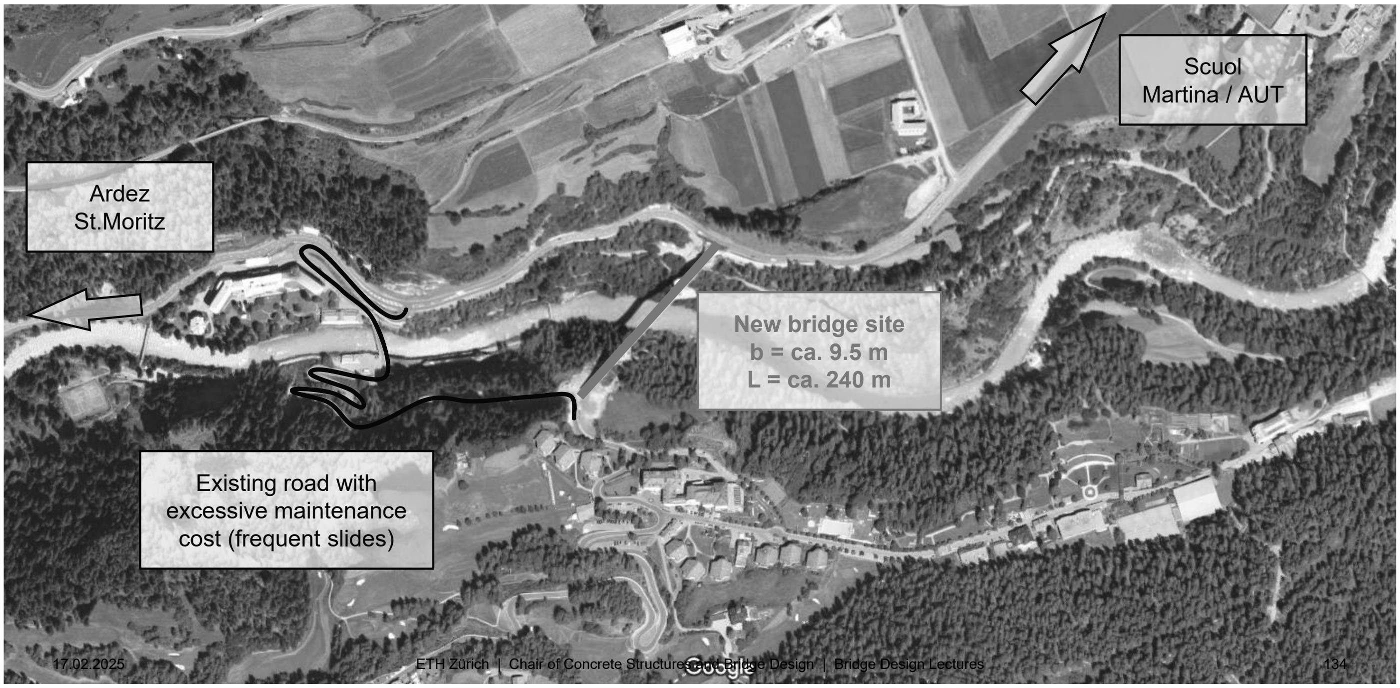
Holistic Design – Example: Obvious (?) solutions



Holistic Design – Example: Obvious (?) solutions



Holistic Design – Example: Starting Point



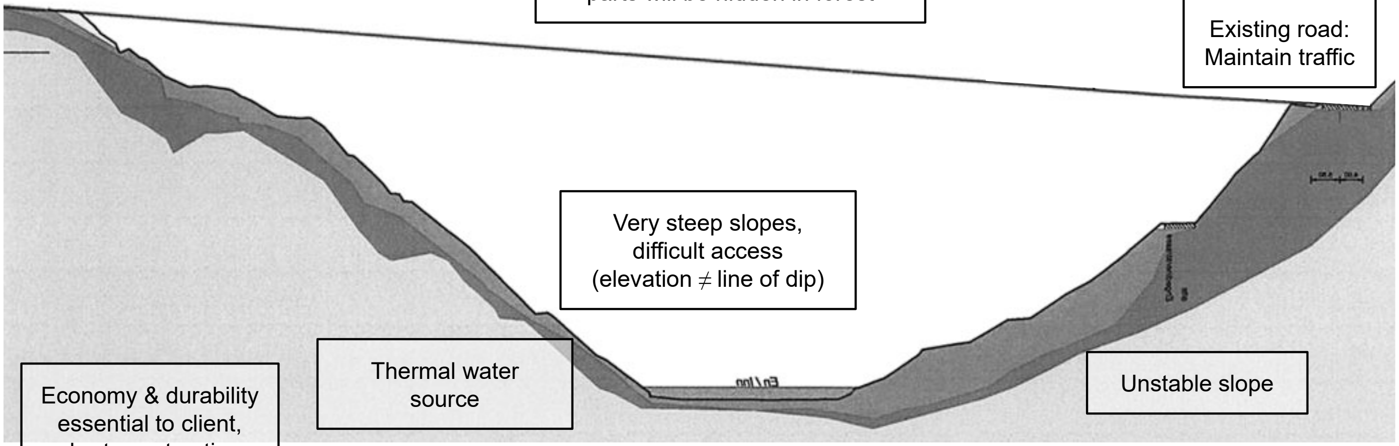
Scuol
Martina / AUT

Ardez
St.Moritz

New bridge site
b = ca. 9.5 m
L = ca. 240 m

Existing road with
excessive maintenance
cost (frequent slides)

Holistic Design – Example: Boundary Conditions



Existing road:
Maintain traffic

Far-reaching impact of new bridge
on the impressive landscape,
parts will be hidden in forest

Existing road:
Maintain traffic

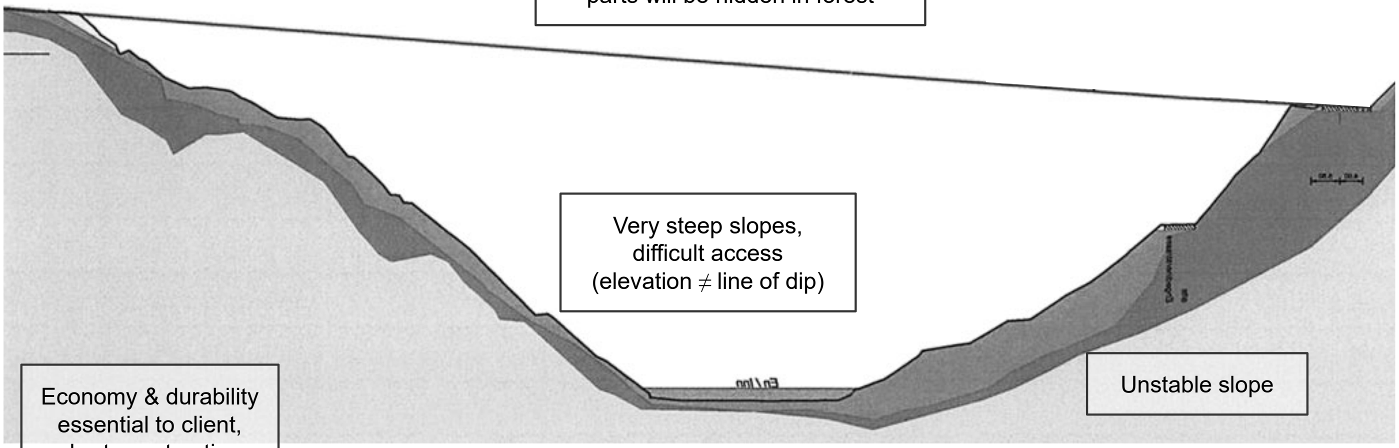
Very steep slopes,
difficult access
(elevation ≠ line of dip)

Thermal water
source

Unstable slope

Economy & durability
essential to client,
short construction
season (1250 m)

Holistic Design – Example: Decisive Boundary Conditions

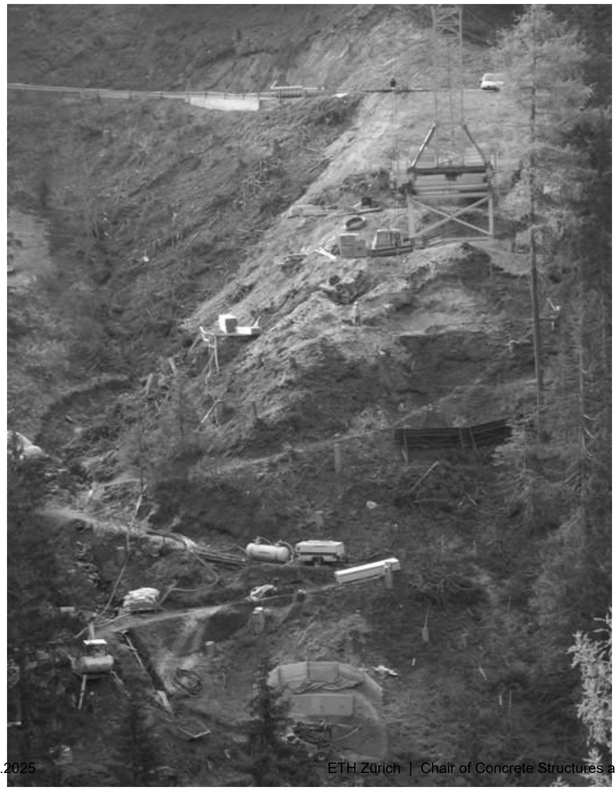


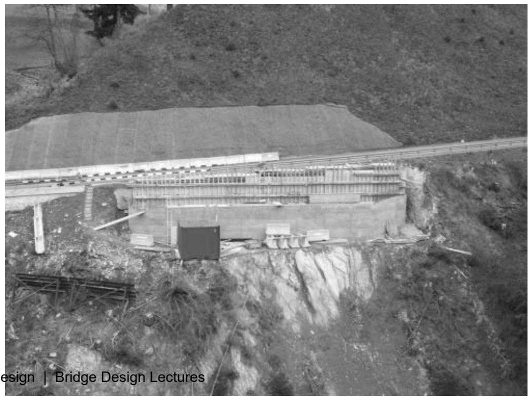
Far-reaching impact of new bridge on the impressive landscape, parts will be hidden in forest

Very steep slopes, difficult access (elevation ≠ line of dip)

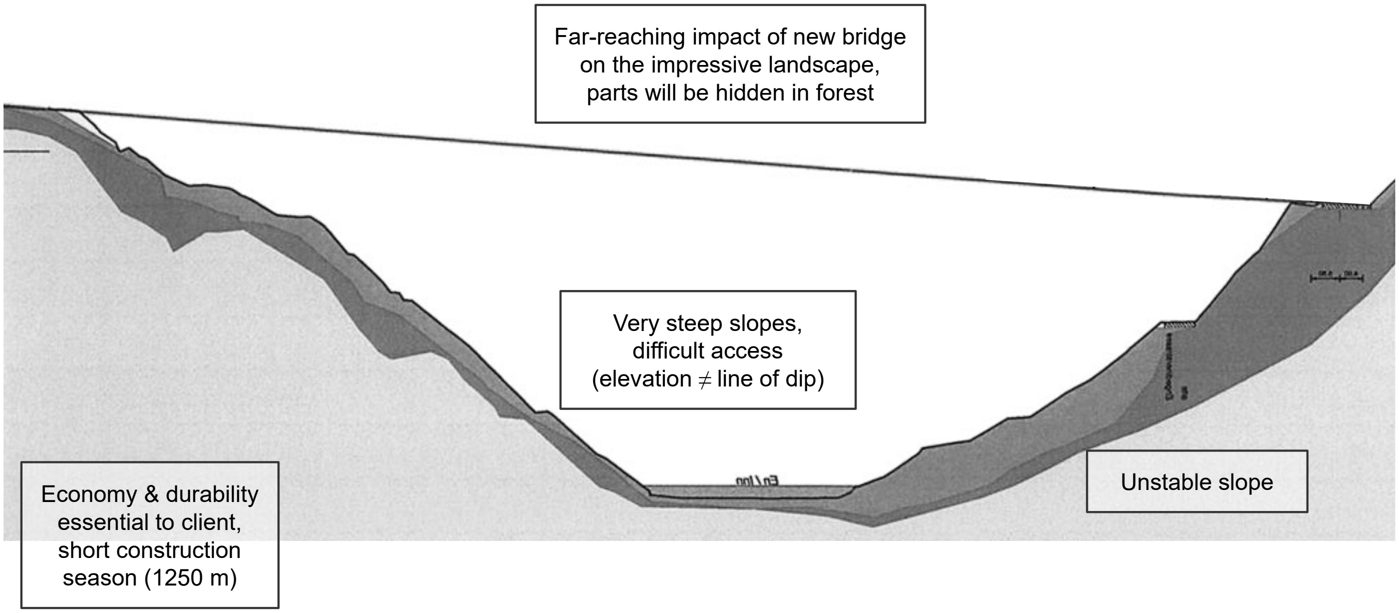
Unstable slope

Economy & durability essential to client, short construction season (1250 m)





Holistic Design – Example: Decisive Boundary Conditions



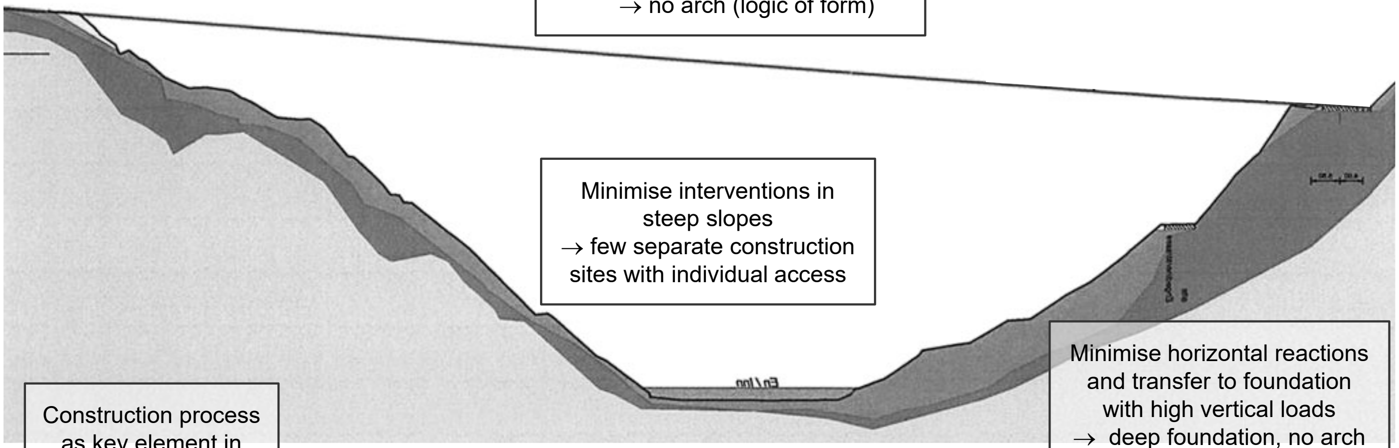
Far-reaching impact of new bridge on the impressive landscape, parts will be hidden in forest

Very steep slopes, difficult access (elevation ≠ line of dip)

Unstable slope

Economy & durability essential to client, short construction season (1250 m)

Holistic Design – Example: Design approach / potential solution



Bridge that integrates confidently in the impressive landscape
→ no spectacular gesture
→ no arch (logic of form)

Minimise interventions in steep slopes
→ few separate construction sites with individual access

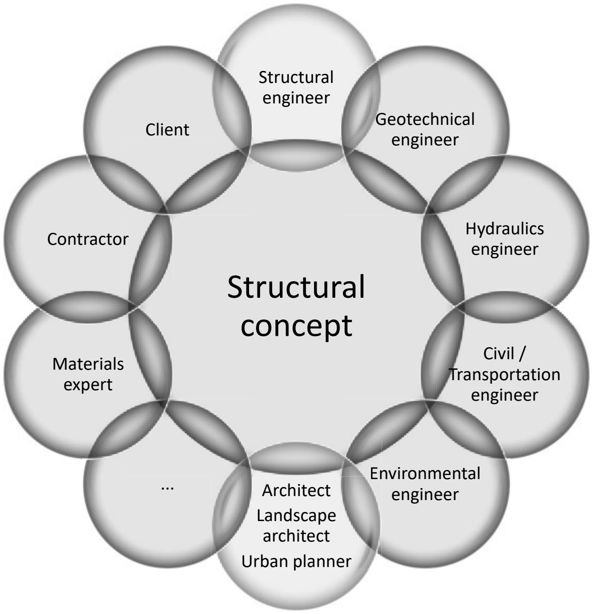
Construction process as key element in conceptual design

Minimise horizontal reactions and transfer to foundation with high vertical loads
→ deep foundation, no arch

Holistic Design – Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓
Design approach / potential solution
↓
Structural concept
↓
Detailing



Structural concept

Structural engineer

Geotechnical engineer

Hydraulics engineer

Civil / Transportation engineer

Environmental engineer

Architect
Landscape architect
Urban planner

…

Materials expert

Contractor

Client

Holistic Design – Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
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Structural concept
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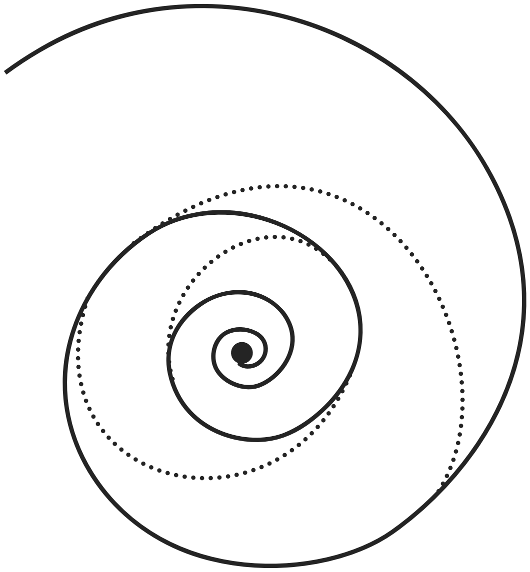
Detailing



Holistic Design – Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
Structural concept
↓
Detailing

"Classical" structural engineering aspects
(safety, serviceability, economy, construction)

Aesthetics
(integration / logic of form / elegance)

Further site- or use-specific aspects
(ecology, traffic, …)

→ Interdisciplinary design team

Holistic Design – Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
Structural concept
↓
Detailing

Design team meetings / workshops

Sketches, pre-dimensioning, mock-ups (physical or virtual) of alternatives

Interdisciplinary – interactive – iterative

Holistic Design – Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
Structural concept
↓
Detailing

Structural engineer, architect and further experts as required develop the structural concept collaboratively, in a dialogue

A “division of tasks” is ill-suited

The collaboration is non-hierarchical

> *“The necessary task is to give attention to places and buildings. That is the task of ‘builders’. And the ‘builders’ are precisely the new profession that must link in a tireless and friendly dialogue the engineer and the architect, the left hand and the right hand of the art of building”*
>
> *(Le Corbusier, 1966)*

The structural engineer and the architect and urban or landscape planner, typically forming the core design team, should develop the structural concept collaboratively with all involved experts in a dialogue, which is best organised in the form of design team meetings or rather design workshops. A formal division of tasks in this early design stage is ill-suited, as it impedes the holistic consideration of all involved aspects.

Metaphorically, a division of tasks in design is like trying to obtain a loaf of bread by first baking the flour, then the water, and finally adding salt and yeast - instead of mixing and kneading the ingredients (in design team meetings), letting them rise (the benefit of inspiration by collaboration, where 1+1 is more than 2), forming and finally baking the loaf. In other words, an approach where the engineer develops the structural concept and the architect refines it – though proposed by an eminent engineer – is equally inappropriate as the one where the architect develops a bridge and the engineer ensures its structural integrity and construction, which is common in signature bridges designed by star architects. Accordingly, it is irrelevant – and in the best case even impossible – to decide which member of the design team contributed the decisive ideas to the chosen concept. To the experience of the author, the best designs with the highest chances of winning a design competition are those where each team member might claim that the final design is his or her personal one.

The collaboration in the interdisciplinary design team should be non-hierarchical, though the structural engineer will typically take the lead in terms of fixing the workshops, and ensuring that the boundary conditions and constraints are respected. To ensure an efficient process, all team members should study the available information before the first workshop, such that the decisive constraints and boundary conditions can be identified and first sketches developed. Typically, several design workshops are required to obtain a convincing design, where the concept is developed initially based on sketches and drawings to scale in cross-section and elevation, and refined using virtual or physical 3D-models. This is, however, no linear process, but rather an iterative one, where different design approaches and potential solutions are typically studied and compared and refined until the best solution has been identified and can be detailed to the degree required.

Holistic Design – Design Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
Structural concept
↓
Detailing

~~«The engineer develops the structural concept, the architect refines it»~~

~~is equally inappropriate as~~

~~«The architect conceives a structure, the engineer ensures its structural integrity»~~

Holistic Design – Design Process

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
Structural concept
↓
Detailing

Design team

High competencies in own field

Interest in, and affinity to other aspects
(common vocabulary)

Ability to discourse in a dialogue

Open-mindedness
(other’s standpoints and ideas)

Depending on the project and its specific constraints, expertise in many different fields is required in order to conceive a bridge. All bridges require competencies in structural engineering, and structural engineers may be able to design convincing bridges on their own. However, even experienced structural engineers typically recur to the expertise of architects and urban or landscape planners in major bridge projects and form an interdisciplinary design team in design competitions, where such teams are nowadays often required by the client. Depending on the project, such teams include – further to the mentioned members – experts in geotechnical engineering, hydraulics, civil engineering, traffic planning, environmental engineering or mechanical and electrical engineers. While large engineering firms cover many of these disciplines in-house, smaller companies often need to team up with specialists in the fields relevant for a specific project. Contractors are involved in the design in case of design-build competitions and should also be consulted in other projects where the construction is challenging. Unless the design competition is anonymous, involvement of the client is also recommended.

Obviously, each of the team members must be highly competent in their own field. In addition, it is essential for a successful interdisciplinary collaboration that all team members are interested in the other aspects of the design such that they share a common vocabulary and are able to discourse in a dialogue. Moreover, the team members must be open-minded hence ready to listen to other’s standpoints and ideas, even in their own field of expertise.

Holistic Design – Design Process

Interdisciplinary design team

Starting point / service criteria

↓

Decisive boundary conditions

↓↑

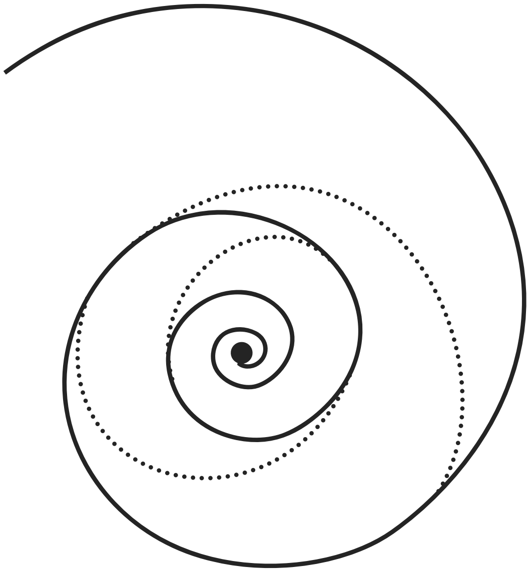
Design approach / potential solution

↓↑

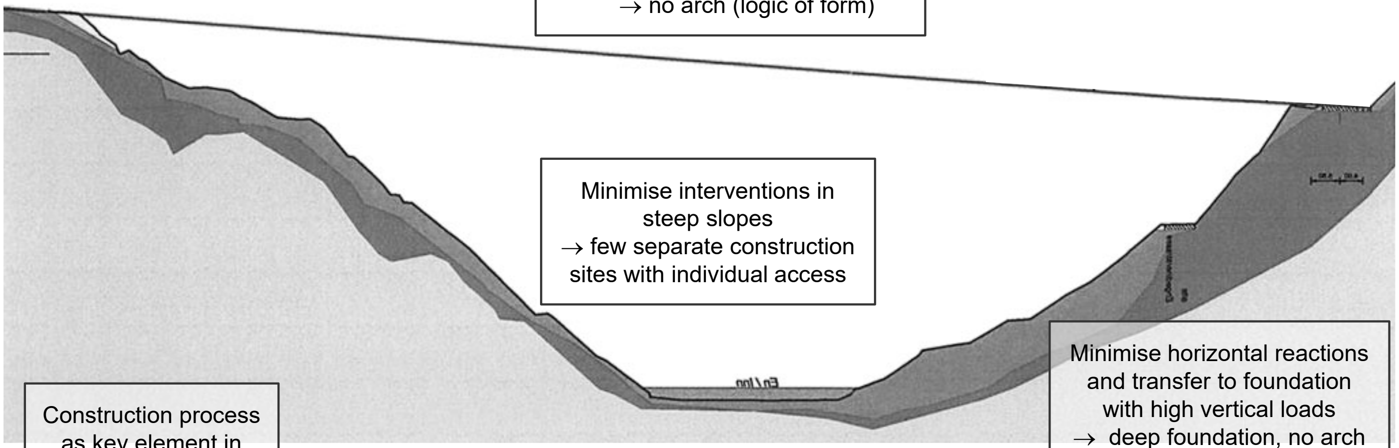
Structural concept

↓

Detailing



Holistic Design – Example: Design approach / potential solution



Bridge that integrates confidently
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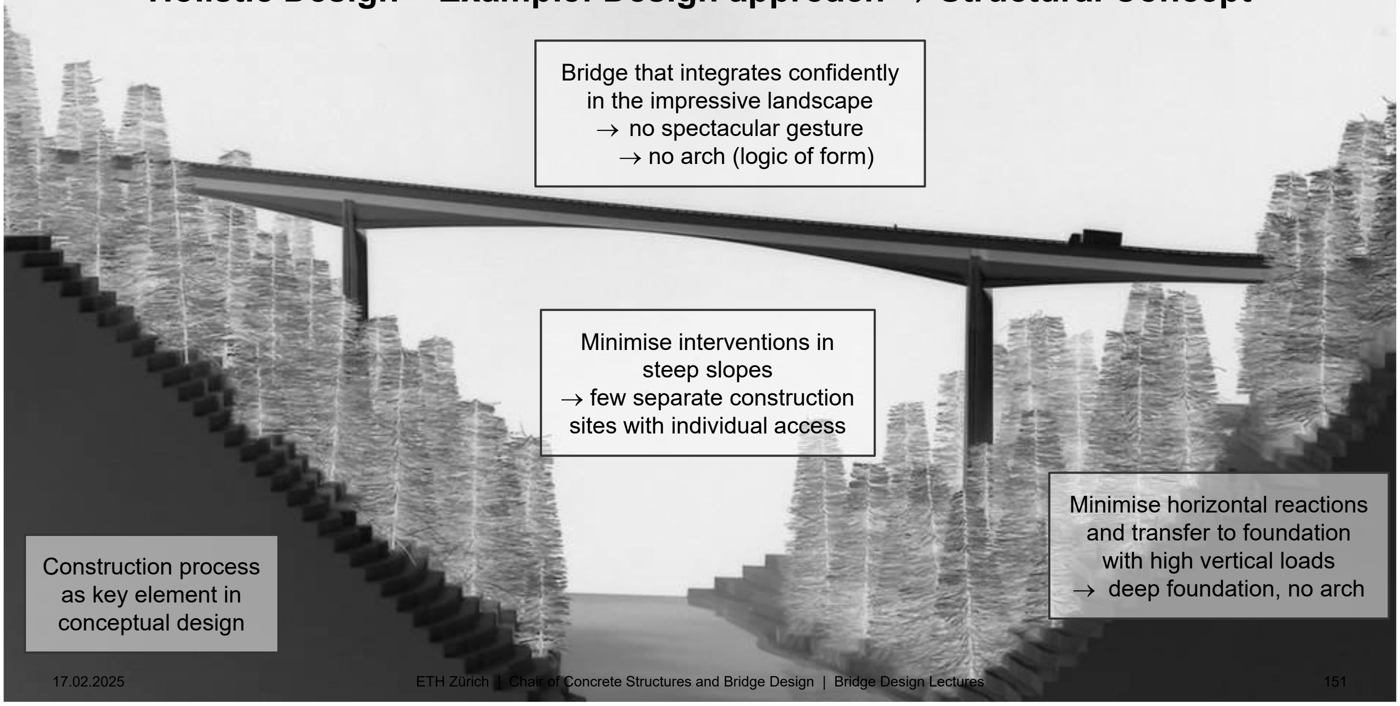
→ no spectacular gesture
→ no arch (logic of form)

Minimise interventions in
steep slopes
→ few separate construction
sites with individual access

Minimise horizontal reactions
and transfer to foundation
with high vertical loads
→ deep foundation, no arch

Construction process
as key element in
conceptual design

Holistic Design – Example: Design approach → Structural Concept



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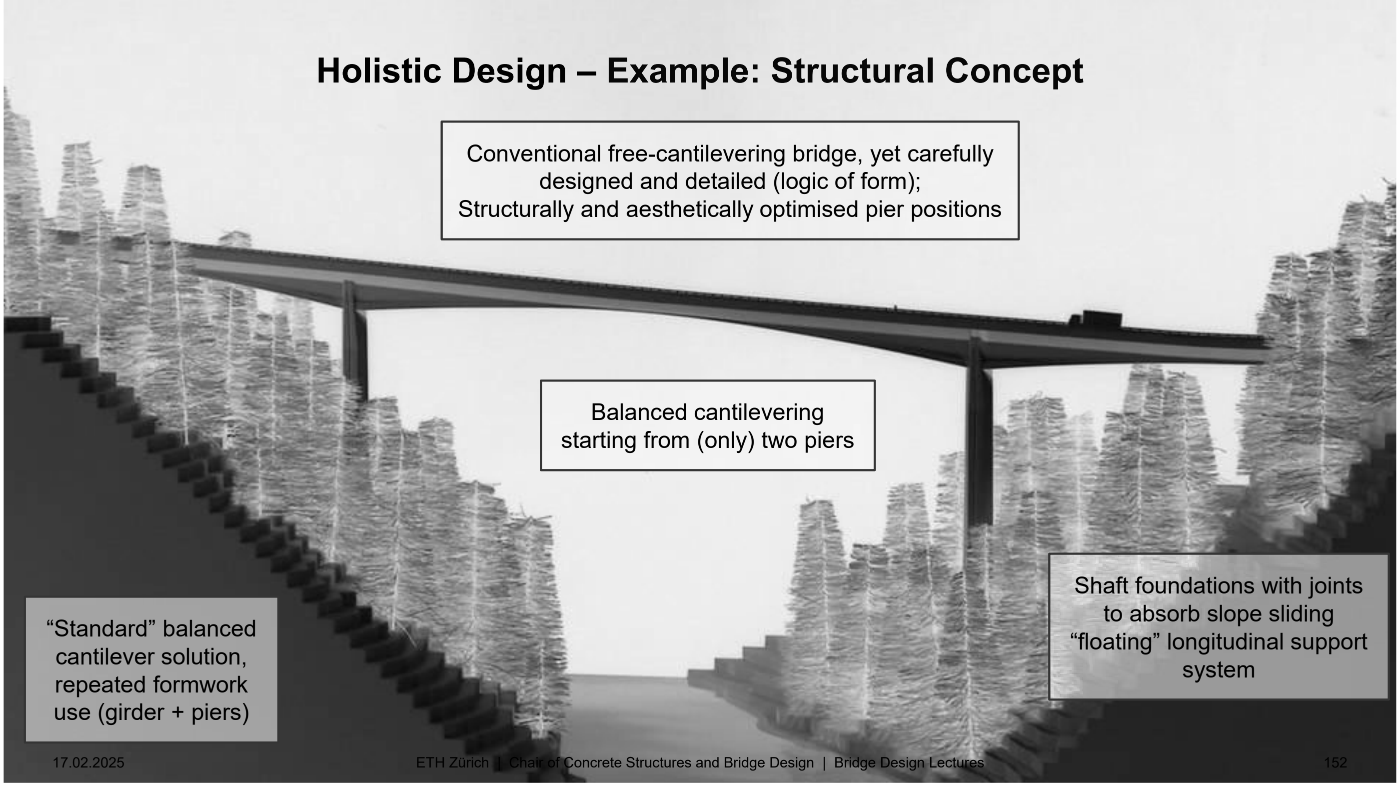
Holistic Design – Example: Structural Concept

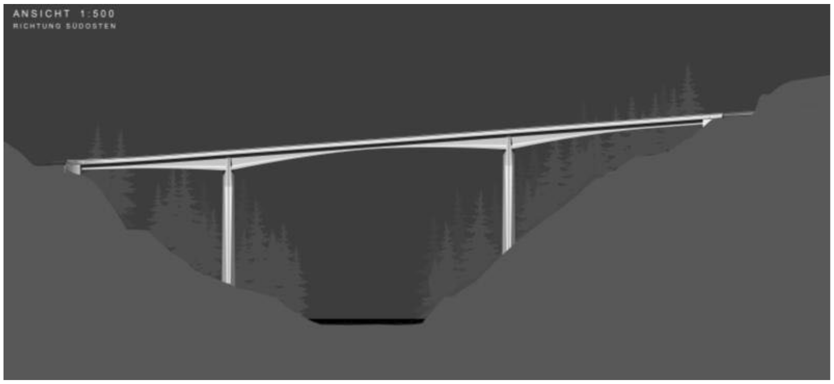


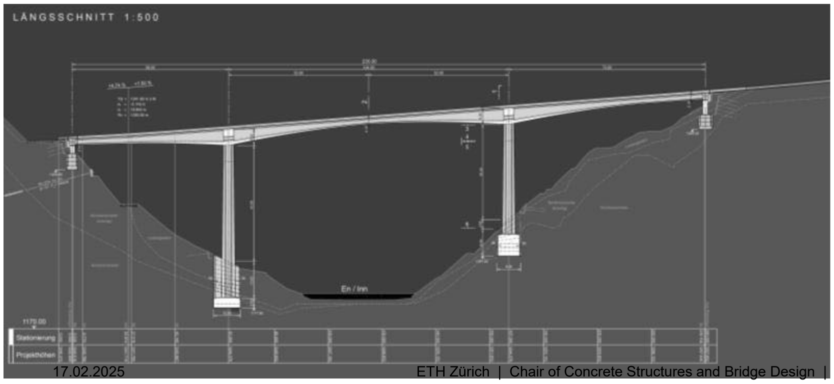
Conventional free-cantilevering bridge, yet carefully designed and detailed (logic of form);
Structurally and aesthetically optimised pier positions

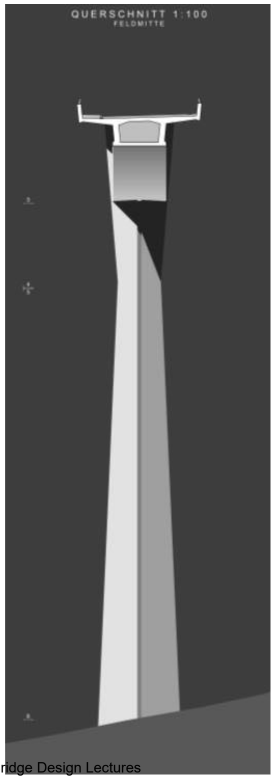
Balanced cantilevering starting from (only) two piers

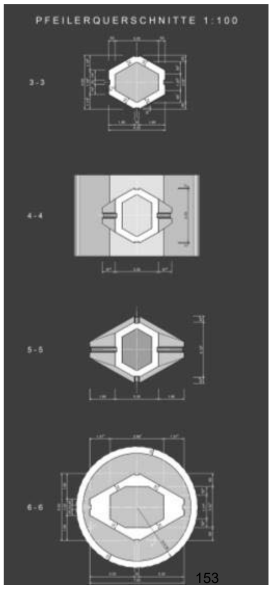
“Standard” balanced cantilever solution, repeated formwork use (girder + piers)

Shaft foundations with joints to absorb slope sliding
“floating” longitudinal support system



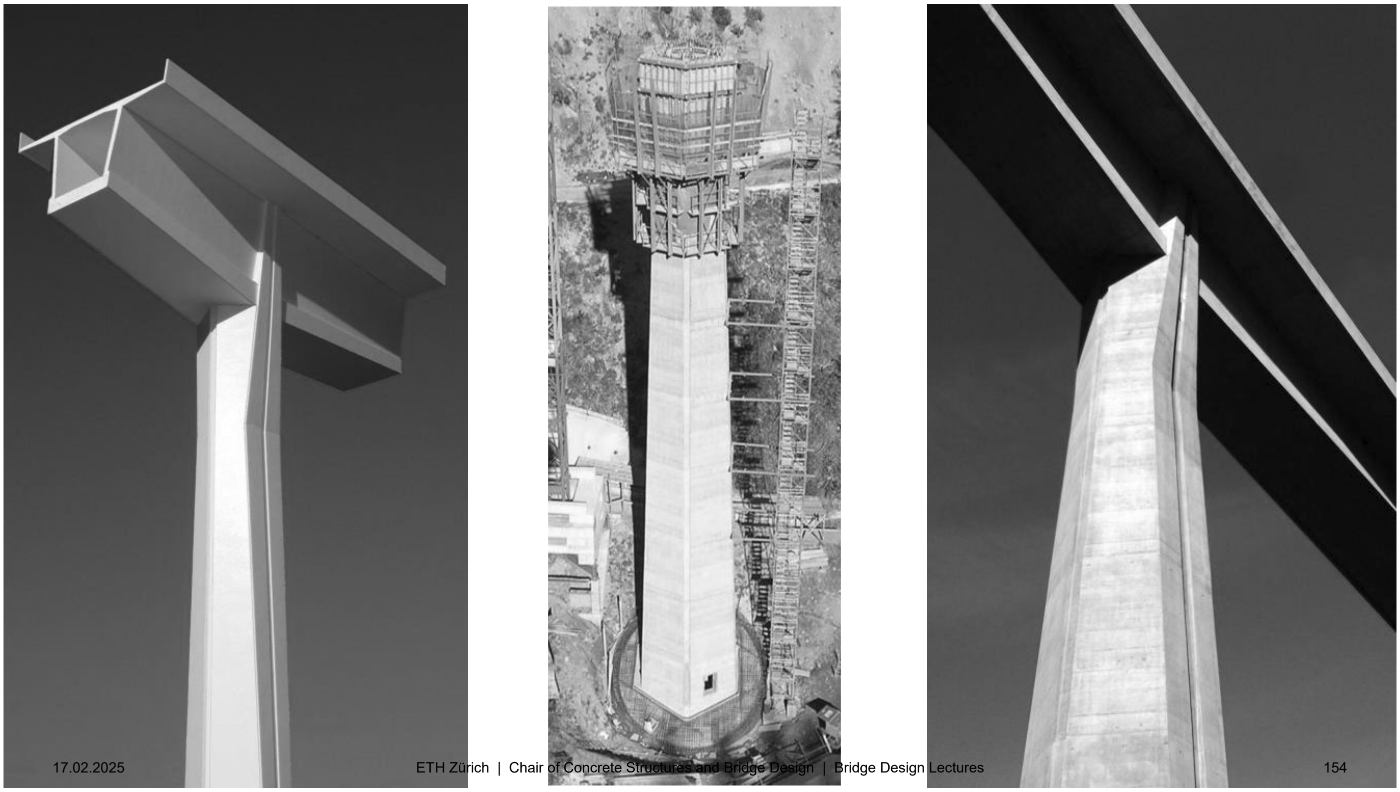




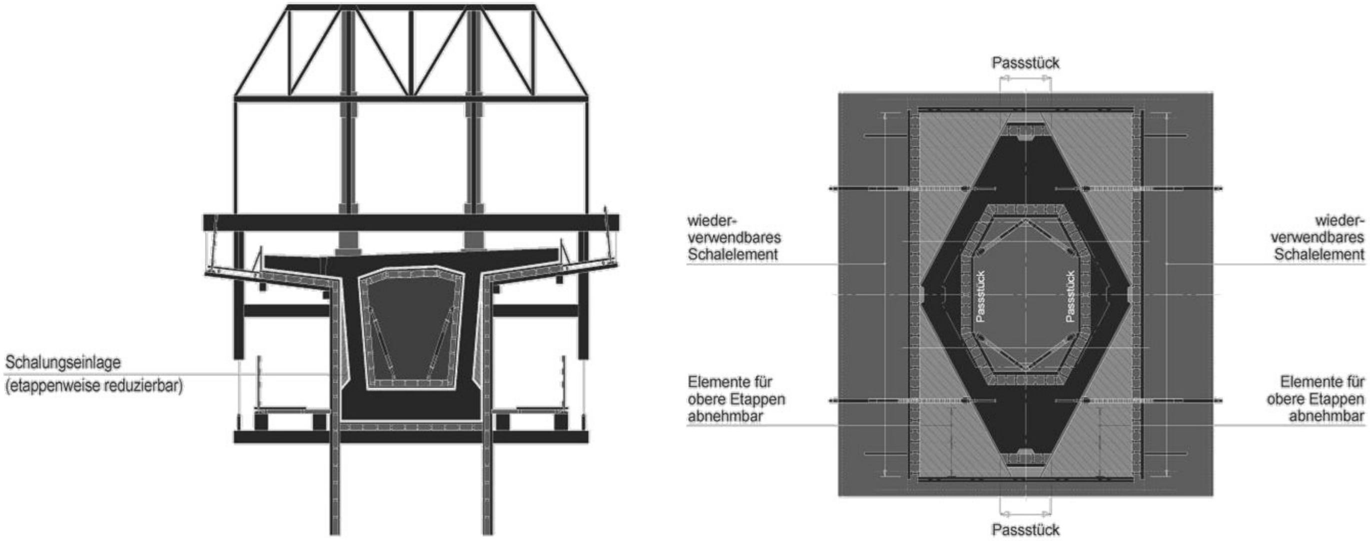


The chosen free-cantilevering bridge is a new interpretation of an old concept – a conventional bridge, yet carefully designed and detailed and optimised with respect to all boundary conditions.

The choice of only two piers lead to a relatively long side span (other proposals in the design competition had 3 piers).



The bottom slab of the girder, with variable thickness, is made visible. It appears to protrude from the web towards the pier, but actually has a constant width (the box bottom width is getting narrower towards the pier)



The careful design and detailing resulted in very little extra cost, since the force flow and the construction process were considered from the very beginning of the design process.

ONE formwork was used for the piers (climbform, only the pieces denoted «Passstück» had to be adjusted when moving it), and ONE formwork for the girder (only the «Schalungseinlage» had to be adjusted).

Execution closely followed the concepts presented in the design competition.

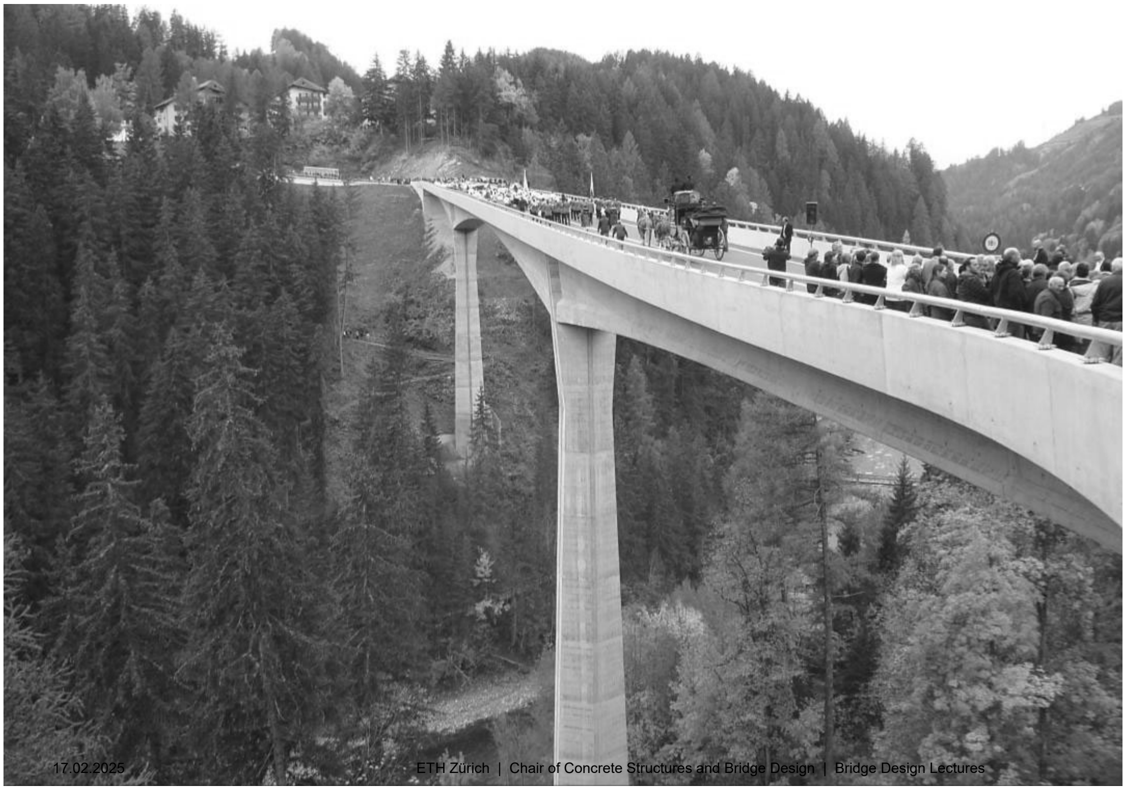
The structural concept was, of course, also heavily influenced by technical constraints. One of the major challenges was the soil-structure-interaction or rather, in this case, avoiding it, This pier was founded 18 m below ground in solid rock, in a shaft with joints allowing to absorb the expected sliding of the slope for 100 years (first use of this concept worldwide: Lehnenviadukt Beckenried, CH).

Balanced cantilevering, basic section (length given by dimensions of the two free cantilevering carriages).

Winter 2008/2009 (construction season only 8 months due to temperature and weather conditions):

100 m girder length (as double cantilevers) 70 m above ground for several months «on ist own».

Remider: Only one formwork was used for the piers, and one formwork for the girder.



The inauguration ceremony showed the high level of acceptance of the local population.

Conceptual Design

Holistic Design – Concluding Remarks
Ganzheitlicher Entwurf – Schlussbemerkungen

Holistic Design – Concluding Remarks

Interdisciplinary design team

Starting point / service criteria

↓

Decisive boundary conditions

↓↑

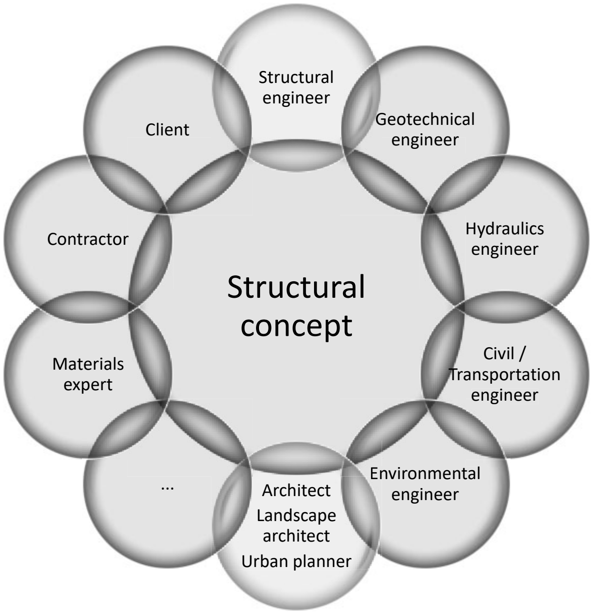
Design approach / potential solution

↓↑

Structural concept

↓

Detailing



Holistic Design – Concluding Remarks

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
Structural concept
↓
Detailing

Depending on the project,
technical or aesthetical aspects are more decisive
for the development of the structural concept

Both aspects should receive a minimum of attention
in all cases to avoid banality and arbitrariness

Irrespective of the importance of structural and
technical or aesthetical aspects,
the structural engineer – who carries the
responsibility – is the author of the project

The designers of this bridge were Michel Virlogeux (structural engineer), in collaboration with Norman Foster (architect). But in public, only the famous architect gets the credit for it. Even among structural engineers, Michel Virlogeux is not very well known. Is this correct?

Photo: https://www.tourisme-aveyron.com/

Responsibility: Construction over (electrified) railway in service.

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Responsibility: Entire basic section, 70 m above Inn river, supported by one steel beam crossing the pier.

Responsibility: Entire basic section, 70 m above Inn river, supported by one steel beam crossing the pier.

Responsibility: Balanced cantilevering 140 m above Karoon river in southern Iran.

Holistic Design – Concluding Remarks

Interdisciplinary design team

Starting point / service criteria
↓
Decisive boundary conditions
↓↑
Design approach / potential solution
↓↑
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↓
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Irrespective of the importance of structural and
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the structural engineer – who carries the
responsibility – is the author of the project

(this does not mean that structural engineers should
strive for fame as “star architects”)