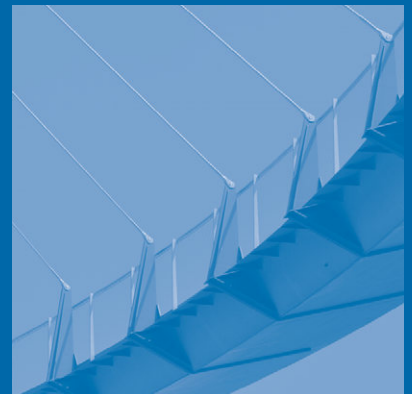
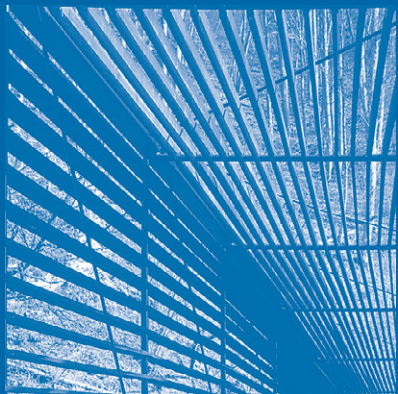


**DETAIL** Practice

# Pedestrian Bridges

Ramps  
Walkways  
Structures

Andreas Keil





**DETAIL** Practice

# Pedestrian Bridges

Ramps  
Walkways  
Structures

Andreas Keil

Edition Detail

## Authors

Andreas Keil, Dipl.-Ing.

### Co-authors:

Arndt Goldack, Dr.-Ing. (Dynamics)  
Sebastian Linden, Dipl.-Ing. (Finishings)  
Christiane Sander, Dipl.-Des. (Lighting)

### Contributors:

Jantje Bley, Dipl.-Ing. (Project Manager),  
Sandra Hagenmayer, Dipl.-Ing.; Frauke Fluhr

## Publisher

### Editorial services:

Steffi Lenzen, Dipl.-Ing. Architect (Project Manager);  
Cosima Frohnaier, Dipl.-Ing. Architect; Sandra Leitte, Dipl.-Ing.

### Editorial assistant:

Carola Jacob-Ritz, M. A.

### Drawings:

Ralph Donhauser, Dipl.-Ing.; Daniel Hajduk, Dipl.-Ing.; Martin Hemmel, Dipl.-Ing.;  
Nicola Kollmann, Dipl.-Ing. Architect; Emese M. Kőszegi, Dipl.-Ing. Architect

### Translation into English:

Christina McKenna, Keiki Communication, Berlin

### Proofreading:

Rachel Hill, Keiki Communication, Berlin

© 2013 Institut für internationale  
Architektur-Dokumentation GmbH & Co. KG, Munich  
An Edition DETAIL book

ISBN 978-3-920034-91-1 (Print)  
ISBN 978-3-95553-147-8 (E-Book)  
ISBN 978-3-95553-158-4 (Bundle)

Printed on acid-free paper made from cellulose bleached without  
the use of chlorine.

This work is protected by copyright. All rights are reserved,  
specifically the right of translation, reprinting, citation, re-use of  
illustrations and tables, broadcasting, reproduction on microfilm  
or in other ways, and storage of the material, in whole or in part,  
in databases. For any kind of use, permission of the copyright  
owner must be obtained.

Typesetting & production:  
Simone Soesters

Printed by:  
fgb freiburger graphische betriebe GmbH & Co. KG, Freiburg  
1st edition, 2013

This book is also available in a German language edition  
(ISBN 978-3-920034-63-8).

Bibliographic information published by Die Deutsche Bibliothek.  
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliographie;  
detailed bibliographic data is available on the internet at <http://dnb.ddb.de>.

Institut für internationale  
Architektur-Dokumentation GmbH & Co. KG  
Hackerbrücke 6, 80335 Munich  
Tel: +49 89 381620-0  
Fax: +49 89 398670  
[www.detail.de](http://www.detail.de)

**Contents**

6	<i>Introduction</i>
	<i>Functional requirements</i>
9	Bridge width
11	Clearance gauge
12	Route layout and access
14	Railings
15	Surfaces
	<i>Statics and dynamics</i>
17	Statics
19	Dynamics
	<i>Materials</i>
27	Wood
28	Stone
29	Concrete
29	Steel
31	Aluminium
31	Glass
31	CFR/GFR
	<i>Design and construction</i>
33	Design
34	Definitions of terms
35	Arch bridges
38	Beam and slab bridges
43	Truss bridges
47	Suspension bridges
53	Cable-stayed bridges
56	Stress ribbon bridges
60	Curved bridges
	<i>Finishing</i>
65	Surfaces
68	Railings
70	Furniture
70	Expansion joints
71	Drainage
72	Bearings
72	Lighting
	<i>Economic aspects</i>
77	Construction principles
78	Costs
79	Life cycle considerations
80	Cost calculations
	<i>Special pedestrian bridges</i>
83	Movable bridges
87	Closed bridges
88	Platforms
	<i>Examples of projects</i>
90	Completed pedestrian bridges
	<i>Appendices</i>
110	Literature, standards
111	Picture credits
112	Index

## Introduction

In recent decades a series of spectacular structures have established the pedestrian bridge as a genre all of its own within the broader field of bridge construction. Built in the most diverse locations, in cities, parks and landscapes, across streets, railways, rivers or canyons, these bridges' striking constructions, interesting trajectories, welcoming qualities and often sculptural appearance are astonishing. Pedestrian bridges have long led a marginal existence and we have only gradually become aware that they could be more than purely functional structures. Pedestrian bridges must of course primarily be functional, but they should also engage with a site's unique features, its routes, topography and context. Their presence in public space offers not only the potential to connect separated spaces, but also to give a place its own identity. During 19th century industrialisation, rolled girders revolutionised bridge building and cost-effective serial structures were developed, meaning that other aspects faded more and more into the background. It was only later that increasing technical progress successfully counteracted this development.

There are fewer restrictive functional and static demands on pedestrian bridges than there are on road and railway bridges. They therefore give designers the necessary freedom to react to a bridge's site and uses and to develop bespoke solutions. Seating, niches, platforms or beautiful views on some bridges can thus be especially welcoming, inviting pedestrians to linger there.

The master builders of the antiquity laid the foundations for bridge construction by developing the load-bearing round arch. They created audacious technical masterworks and succeeded in building imposing bridges with large spans, which

were funded by ambitious clients whose names remain inseparably linked with the bridges. The situation is no different today: an ambitious planner needs the backing of a committed client to achieve a successful result. Only then will they achieve their shared goal of creating something beautiful as well as useful. Highly complex projects in particular – whether structurally or organisationally complex – run an increased risk of encountering unexpected problems; they require a high degree of cohesion and the willingness of all involved to overcome very difficult phases of the project. Successful structures rarely result from the work of one individual; they require committed and motivated clients, planners and contractors.

Interdisciplinary collaboration between architects and engineers is also important in bridge construction – to a different extent than is the case in other civil engineering projects. Engineers need to engage intensively with the structure's design as well as with the purely economic and structural aspects in developing support structures. They must think in terms of variations and justify decisions made from the complete range of possibilities, penetrating and understanding the context. These skills used to be – and still are – inadequately taught in engineering training; this inadequacy can be seen in some small and medium span bridges.

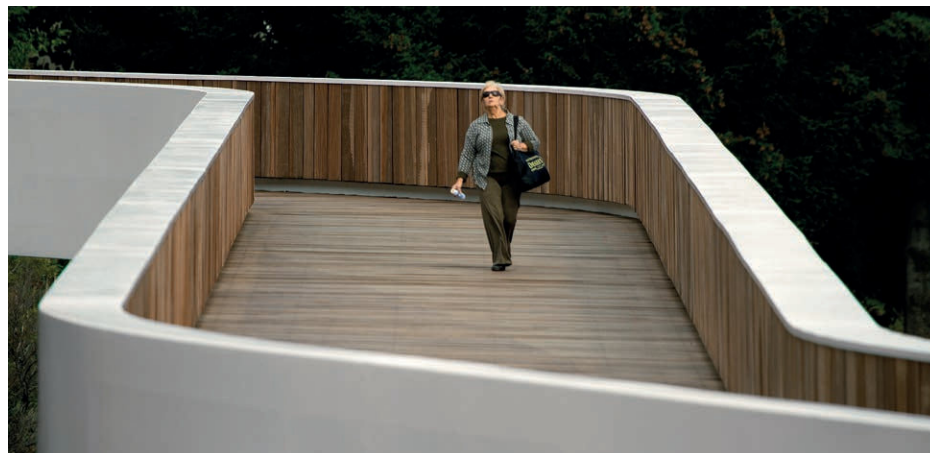
Architects must engage with a bridge's urban context, its formal language and the arrangement of its details. A high degree of sensitivity to design is essential in creating a good pedestrian bridge, especially if it is to be installed in a central urban area or special landscape. Architecture is indivisible, so it relies on a respectful and trusting discourse between the two disciplines; an approach

that is free of vanity and remains focused on the design, allowing everyone involved to join forces to develop good, beautiful solutions. Many outstanding structures – especially pedestrian bridges – prove that this discourse is already ongoing in some areas. Many of the pedestrian bridges portrayed in this book have been developed in competitions by architects and engineers working successfully together and complementing each other.

The often daring constructions of the antiquity did not rest on any particular methods of calculation. Their construction was based on empiricism and painful experience and often cost many human lives. Only at the end of the 16th century did Galileo Galilei formulate the first principles of structural engineering and lay the foundations for scientific structural engineering, which was further developed by mathematicians such as Isaac Newton, Gottfried Wilhelm Leibniz, Jacob Bernoulli and Leonhard Euler. This represented a decisive step away from craftmanly, empirical and intuitive bridge building to more precisely calculated engineering and technology-based construction.

In today's digital era, computer programmes can be used to very quickly carry out parameter studies, optimising a structure's design so that ideas can be quickly confirmed or discarded. Computer programmes can also precisely calculate a structure's dynamic behaviour. Synchronisation phenomena, which have recently occurred in various bridges, can be simulated, their causes and effects and the effectiveness of measures taken understood. This is an essential prerequisite for the construction of light and filigree pedestrian bridges. Furthermore, the computing capacity available today leads some planners to

1 Pedestrian bridge over the Carpinteira River, Covilhã (P) 2009, João Luís Carrilho da Graça



design structures down to the last detail at a very early stage of planning, generating immense quantities of data. This means that the results cannot be completely comprehended in detail so it can be easy to lose sight of the essentials and first principles.

The evolution of bridge construction, ranging as it does from a simple tree trunk laid across a stream through to today's spectacular three-dimensional support structures, has been a long one. New materials, methods of calculation and manufacturing techniques have repeatedly resulted in milestones in bridge construction over the centuries. These developments have been driven by a desire for more mobility, often for economic and usually for peaceful reasons, but sometimes also for imperial and military ones. Each type of bridge – the beam bridge, the arched bridge and the suspension bridge – has its own history.

The main materials used to build bridges used to be wood and stone, but since the 19th century, steel and concrete have predominated in bridge building. Although concrete has positively influenced construction, with engineers such as Robert Maillart, Ulrich Finsterwalder and Eduardo Torroja in particular showing the potential of this material, it has also contributed to cost effectiveness becoming the priority, although it means that more materials are used (and wasted) than really necessary, especially in road bridge construction. It is a misconception to think that it is less expensive to choose a simple form that requires more materials as it has a greater dead load. In contrast, structures that trace the flow of force and look more appropriate and well-proportioned require less material but are more complicated to manufacture.

Apart from concrete, steel has particularly influenced bridge construction, be it construction steel, steel cables or reinforced steel. Steel is now the main material used for pedestrian bridges. Bold, breathtakingly light structures testify to this material's potential. Continuing progress in the development of material properties as well as in manufacturing, joining and installation technologies, has produced three-dimensional support structures that can be made with great geometrical precision. Cast steel has long since shed the stigma of being brittle and is now often used at complex points in building pedestrian bridges because it is just as tough and weldable as normal mild steel.

Experience has shown that it takes a long time to develop new construction materials as great demands are placed on them and numerous safety tests must be carried out. They must be investigated in terms of strength, cross-section design, joining technology, ease of installation and durability. Universities are currently conducting intensive research into new materials, in particular into plastics, which would seem to have great advantages in terms of durability and strength. A few prototypes have already been built using them so that they can be tested under long-term load stress. However steel is unlikely to be replaced in the near future by new materials in bridge construction, whether for high-strength tension elements or superstructures.

This book provides architects, engineers and technicians as well as manufacturers and interested clients with an overview of current pedestrian bridge construction trends. It is divided into seven chapters and supplemented with illustrations, tables and drawings. The chapter topics range from an outline of the basics and

descriptions of individual materials, an introduction to various types of bridge structures and considerations of the economic aspects of manufacture and maintenance, to an overview of outstanding bridge structures. The book concludes with a documentation of selected pedestrian bridges, providing an insight into the diversity of pedestrian bridge construction.

This book offers practical assistance with design issues and will hopefully motivate builders and designers to try new things in the fascinating field of bridge construction.



## Functional requirements

Pedestrian bridges have the primary function of allowing people to pass safely over obstacles. In contrast to road and railway bridges, pedestrian bridges not only have to connect two places with each other by the shortest route, but people also directly experience them by touching them and walking on them. Well-chosen paths and delightful views enhance a pedestrian bridge's spatial qualities. It is therefore all the more important that a bridge's functional requirements be exactly analysed and defined to form an individual basis for its design. Apart from the geometric properties of the bridge itself, such as width and gradient, the requirements resulting from the obstacles to be crossed, such as the clearance gauge, must also be defined. Safety aspects such as slip resistance and guard rails must also be taken into account.

### Bridge width

A bridge's width is determined by its use. In Germany, figures and reference values published by the Road and Transportation Research Association (Forschungsgesellschaft für Straßen- und Verkehrswesen – FGSV) in its recommendations for pedestrian traffic facilities (»Empfehlungen für Fußgängerverkehrsanlagen« – EFA) provide guidelines in this area. EFA defines basic requirements for pedestrian infrastructure facilities, deals with different characteristics of pedestrian traffic, and explains fundamental planning principles. According to EFA a path's width will depend on whether it is to be used purely as a cycle path, a foot path or a mixed-use path. A width of 1.80 m is recommended for footpaths, cycle paths should be 2 m, and shared pedestrian and cycle paths 2.50 m wide. Additional space may be required for open spaces in front of shop windows, at transport stops or for benches, but

these aspects will not have to be taken into account to the same extent in pedestrian bridge construction.

DIN 18 024-1 on »Barrier-free Construction« makes further very general stipulations on the minimum width of barrier-free routes in public spaces. It prescribes total widths of 2 to 3 m, which result from the movement area of 1.20 to 1.50 m required by wheelchair users, plus the necessary meeting and passing spaces.

These specifications are however subject to international variations. In Great Britain widths of 1.80 to 2 m for pedestrian and cycle paths are acceptable, while Australia prescribes widths of up to 3 m (Fig. 1).

A bridge's width is however not defined only by its use; its dimensions should also fit in well with other design and urban planning factors. A bridge's width also has a direct impact on the cost of its manufacture.

Pedestrians usually move at speeds ranging from 0.50 m/s (30 m/min) to 1.80 m/s (108 m/min), depending on whether people are moving in commuter, shopping or event traffic. Depending on the kind of pedestrian traffic and its speed, there are appropriate reference values for concentrations that specify how many people should be on each 1 m<sup>2</sup> of bridge. The basic rule that applies to all types of pedestrian traffic is that the denser the traffic, the more slowly it moves forward. The load-bearing capacity of a pedestrian bridge is calculated as follows:

$$Q = v \cdot d \quad [P/m \cdot s] \quad (I)$$

Q Flow rate [P/m · s]

v Traffic velocity [m/s]

d Traffic density [P/m<sup>2</sup>]

standard	country	min. path width [m]	clearance [m]	max. gradient [%]
Austrroads 13, 14, 92	Australia	1.5–1.8 (Pedestrians) 1.5–3.0 (Cyclists) 2.5–3.0 (Mixed)	2.1–2.4 (Pedestrians) 2.5–3.0 (Cyclists)	12.5 (Pedestrians) 5.0 (Cyclists) 3.0 (Mixed)
Structures Design Manual	Hong Kong	2.0 (Pedestrians) 3.0 (In metro stations)	–	5.0–8.3 (Pedestrians) 4.0–8.0 (Cyclists)
Japanese Footbridge Design Code (1979)	Japan	3.0 (Pedestrians)	–	5.0
Design Specifications of Road Structures	South Korea	1.5–3.0 (Pedestrians) 3.0 (Cyclists)	2.5	–
British Standard 5400	Great Britain	1.8 (Pedestrians) 2.0 (Mixed) 2.7 (Pedestrians and cyclists with separate path)	–	5.0–8.3 (Pedestrians)
DIN 18024-1	Germany	2.0 (Pedestrians) 3.0 (Mixed)	2.5	6.0

Functional requirements  
Bridge width

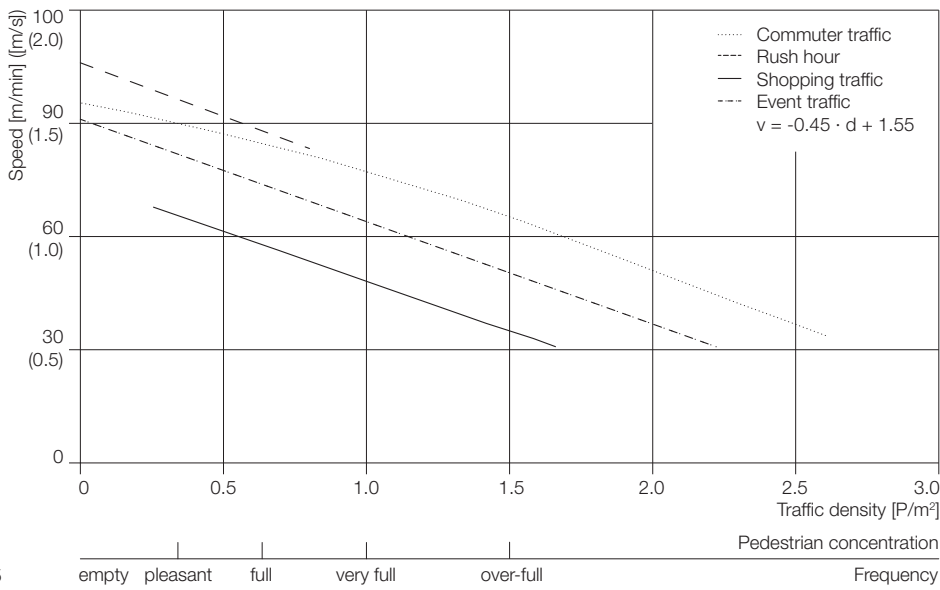


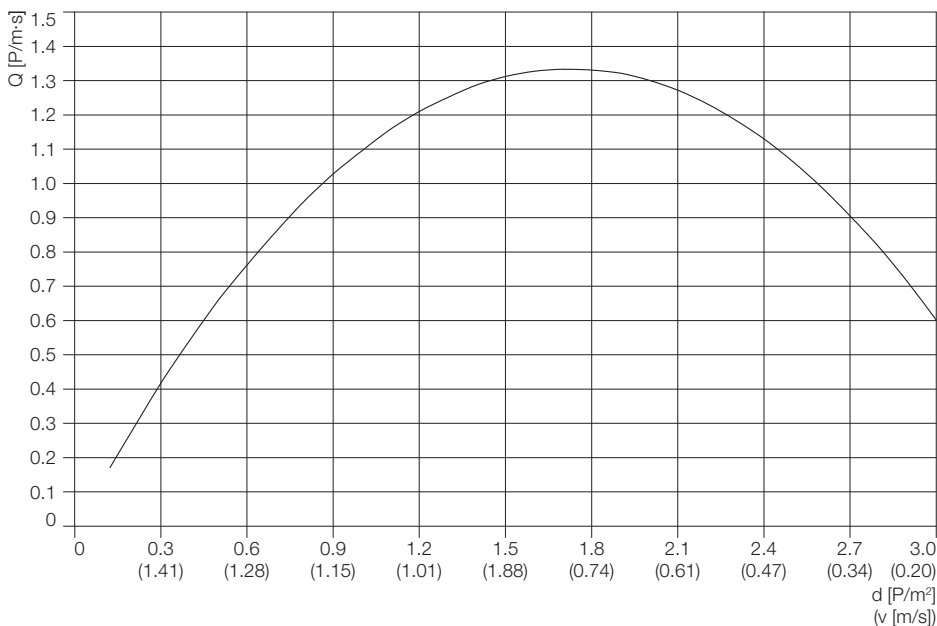
Fig. 5 shows dependencies of various pedestrian flows, which can be defined in a linear relationship between traffic density and speed. In the case of event traffic for example, the following function results.

$$v = -0.45 \cdot d + 1.55 \text{ [m/s]} \quad (II)$$

If you are designing a pedestrian bridge with a maximum flow capacity,  $Q$ , for a certain type of pedestrian traffic, the density and speed at which this value is at its maximum must be identified. Using (II) in (I) results in a quadratic function for event traffic (Fig. 6).

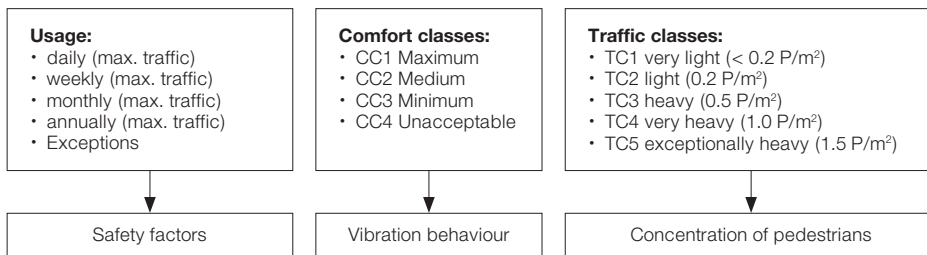
$$Q = -0,45 \cdot d^2 + 1,55 \cdot d \text{ [P/m} \cdot \text{s]}$$

This function has its maximum at a speed and related density of  $v = 0.78 \text{ m/s}$  and  $d = 1.72 \text{ P/m}^2$ . Its capacity would therefore be 4,829 P/h per metre of bridge width. Conversely, a bridge's required width can be calculated based on the capacity called for. If the requirement is, for example, that 15,000 people should be able to leave a large-scale event within 10 minutes, the pedestrian bridge will have to be 18.63 m wide. It should also be noted that these are maximum values, which should be used to manage large numbers of pedestrians and prevent the risk of panic breaking out in very dense crowds of people.



Many pedestrian bridges rarely or never reach the limits of their capacity. Their function does however often determine their width, ensuring that pedestrians or pedestrians and cyclists can move easily on the bridge without getting in each other's way. This results in most cases in usable widths of 2.50 to 3.50 m.

While static loads do not depend on a bridge's use, it is recommended that



7

distinctions be made between various design situations in considering dynamic aspects.

A distinction is made between traffic classes, which basically define concentrations of pedestrians, and comfort classes, which determine how much a pedestrian bridge can be allowed to vibrate and what speeds are permissible on it. These traffic classes are divided into five categories ranging from very light traffic with a density of less than 0.2 P/m<sup>2</sup> up to exceptionally heavy traffic of 1.5 P/m<sup>2</sup>. The comfort classes are divided into four categories defining requirements on the dynamic behaviour of bridges. Class CC1 allows for lots of movement, in a suspension bridge for hikers, for example. By contrast, Class CC4 allows only very slight movement, for inner-city bridges, for example (Fig. 7).

These classifications must be individually applied depending on the planned use of the bridge and dynamic considerations then based on them. This approach is not regulated in any particular standard; it was developed based on the results of the research project RFS-CR-03019 »Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Footbridges (SYNPEX)« [1].

### Clearance

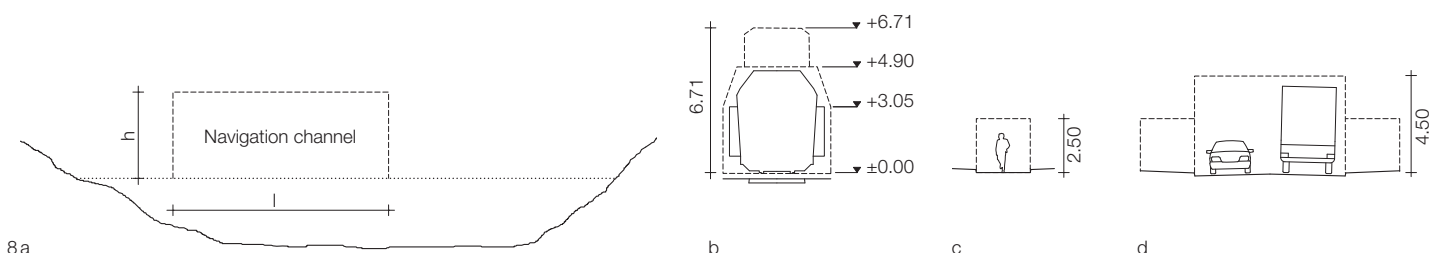
Pedestrian bridges cross a very diverse spectrum of obstacles, ranging from valleys and rivers, roads and paths right up to railway lines. A clearance gauge is defined for all existing traffic routes. A clearance gauge is a line defining an open space that must be kept free of objects of any kind, including built structures. Fig. 8 shows typical clearances for waterways, railway tracks, roads and paths. The clearance gauge prescribed for the traffic route or waterway to be crossed will determine a bridge's height in many cases. The clearance gauge for a waterway also depends on the highest water level of the river being crossed. Depending on use of the route as a road or railway line or for shipping, adjacent structural elements must also be designed to take impact loads. Compared with other impacts on a pedestrian bridge, these loads are very high and can thus determine dimensions in a bridge's design. It is advisable to avoid positioning structural elements in these critical areas as far as possible in the design. A clearance gauge often has to be maintained during construction and may only be lifted for very brief breaks, which can have decisive effects on the process of manufacturing and installing a bridge.

- 1 Overview of common standard rules for pedestrian bridges worldwide
- 2 Pedestrian bridges with light traffic: comfortable free movement and overtaking is possible.
- 3 Pedestrian bridges with heavy traffic: Free movement is possible; overtaking may be restricted at times.
- 4 Pedestrian bridges with very heavy traffic: Free movement is restricted; overtaking no longer possible.
- 5 The relationship between speed and traffic density depends on the type of traffic
- 6 Capacity Q in persons per second per metre of bridge width
- 7 Marginal conditions for footbridge design
- 8 Typical clearance gauges:
  - a River; b Rails; c Footpath; d Road

### Waterways

Depending on the extent and type of use by shipping, rivers and canals are subject to a range of very different clearance requirements, which are prescribed by local offices of the Waterways and Shipping Administration (Wasser- und Schifffahrtsämter – WSA). For some rivers there is no specified clearance gauge, on others they cover the waterway's entire width.

It may also be partly necessary to keep banks clear to prevent damaged ships from endangering a pedestrian bridge's stability. On some shipping routes there are also "danger zones": if parts of a bridge's support structure are positioned in these zones, they and the bridge must be able to bear the impact of a collision, which is simulated either through a single static load or by compensation (dissipation) by a prescribed impact absorption. This is designed to prevent bridges from collapsing if, for example, a ship's superstructure is torn off while the ship is passing under the bridge. It is often advisable to avoid these large impact loads and danger zones, even if the consequent higher position of the superstructure results in longer ramps.

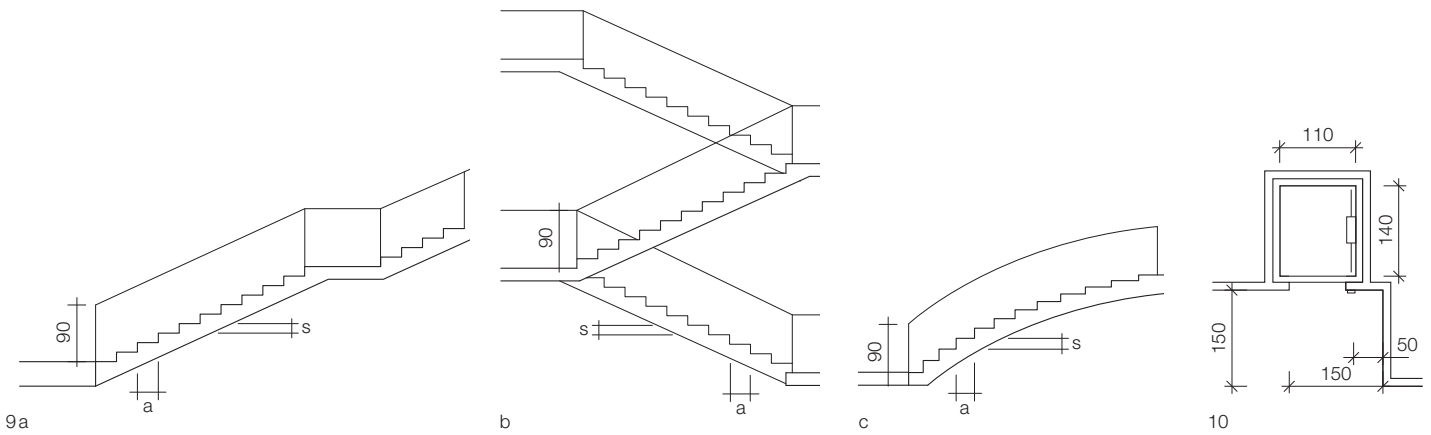


8a

b

c

d



**Railway lines**

Pedestrian bridges near railways bear the risk of people coming into contact with live electrical parts and being injured as a result. Protective measures such as distance or barriers must be adopted to prevent this from occurring. A protective distance from live parts accessible to contact is regarded as sufficient when there is a radius of at least 3.50 m from where a person would be standing. The DIN EN 50 122-1 standard on »Railway applications – Fixed installations – Electrical safety, earthing and the return circuit« provides more precise details on this topic. If this distance cannot be adhered to, barriers preventing direct contact must be installed. Their implementation depends on the position of the bridge floor and the distance between the barriers and the live parts. The dimensions of barriers must be chosen so that the live parts accessible to contact cannot be unintentionally touched by someone reaching out in a straight line.

The Federal Highway Research Institute (Bundesanstalt für Straßenwesen – BAST) publishes »Civil Engineering Specification Diagrams«, (»Richtzeichnungen für Ingenieurbauten« – RiZ-ING), while the German railway company, Deutsche Bahn,

regulates such matters in its guideline 997.0101 and specification diagrams EBS 02.05.19. Barriers to prevent people from touching live parts can be installed in the form of horizontal or vertical obstacles, such as plates that function as spacers. Since these elements can also influence a pedestrian bridge's design, such measures should be appropriately implemented in coordination with the relevant specialist departments. Planners should take advantage of the leeway available to them in choosing the type of construction and materials.

In the case of tramways, the regulations and requirements of individual local operators apply. Here too, there are few restrictions in regard to materials; concrete and steel as well as glass can be used. Apart from incorporating elements to protect against accidental contact with live components, bridges that cross electrified railway lines must be grounded.

This means that it is necessary to install grounding rods at the lower edge of the superstructure near the rails and connect them with the rails by means of conductive transverse sections, using welded reinforcement rods running through the structure, for example.

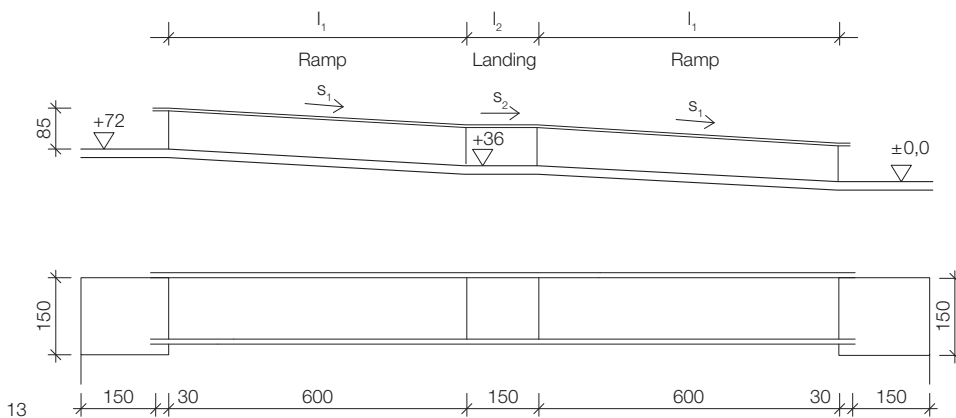
**Traffic routes**

A clearance gauge of 2.50 m is prescribed for pedestrian bridges. While this is easily achieved with beam bridges, it can greatly influence the geometry and form of bridge support structures, in particular of curving cable bridges and arched bridges. A clearance gauge of 4.50 m is usually prescribed for roads for vehicle traffic, but a clearance gauge of 4.70 m may also be stipulated so that subsequent road resurfacing can easily be carried out.

**Route layout and access**

The highest priority in building a pedestrian bridge is to bring people from one place to another – over a river, a road or a valley – by the shortest possible route. Architects and engineers must therefore create the shortest possible access paths and an appropriate route layout. When designing the layout of bridges and ramps it is advisable to incorporate flowing paths and to avoid hazardous corners and turns, especially for cyclists. Because pedestrian and cycle traffic moves at slow speeds, there are few limitations in terms of the radius of curvature. A wide range of free forms can be used, so narrow curves and multi-armed ramps





13

that optimally connect to existing networks of paths can be chosen. Breaking out of two-dimensionality into the third dimension can also result in exciting spatial structures. A pedestrian bridge's superstructure can be freely formed and strongly curved in its layout, making crossing a bridge a unique spatial experience for pedestrians (see Design and Construction, p. 60ff.).

#### Stairs

Germany's restriction on the permitted ramp gradient of 6% often makes for long access paths to bridges, such that it can sometimes be expedient to offer direct and quick access by providing stairs as well as a ramp.

DIN 18065 on "Stairs for buildings" (»Gebäudetreppen«) regulates the form of such stairs, providing precise details on their geometry, the formation of steps, gradients, landings and railings.

The following values are stipulated:

- Staircase pitch  $s$  of at least 14 cm, or a maximum of 19 cm
- Stair tread  $a$  of at least 26 cm, or a maximum of 37 cm
- Rise-to-run ratio of 59 to 65 cm in

accordance with step length measurements  $2s + a$  ( $s$  = rise [cm];  $a$  = tread run [cm])

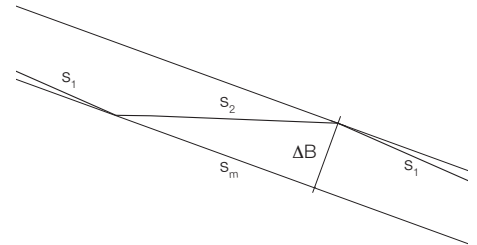
- Minimum useable flight width  $r$  of 100 cm
- If there are more than 18 steps, intermediate landing with a length of 90 cm is required
- Handrail on both sides at a height of 85 cm above the deck surface

Possible stair construction variants range from single-flight stairs through spiral or platform stairways up to Laurin stairs, which have variable gradients and riser heights (Fig. 9).

#### Lifts

If a ramp cannot be installed due to lack of space, a bridge can be made barrier-free with a lift (Figs. 11 and 12). Lifts in public space must be very robust (to withstand vandalism for example) and operational safety and failsafe functioning, especially during operation at night, must also be taken into account.

Rules on barrier-free building included in DIN 18024 apply to the dimensions and design of lifts. A lift car must have a minimum clear width of 110 cm and a clear depth of 140 cm for it to be suitable for



14

wheelchair users, so that there is room for up to two people standing and one person in a wheelchair (Fig. 10).

#### Ramps

The length of an access ramp will result from the prescribed clearance gauge, the bridge's construction height and the permissible gradients (Fig. 13). A ramp can basically have a maximum gradient of 6% so that it meets the requirements of people whose mobility is restricted. In Germany this is regulated by DIN 18024-1. Other countries apply different values. In Australia for example, a gradient of 12.5% is allowed for footbridge ramps (Fig. 1, p. 9). It can often be difficult to directly connect a ramp to an existing network of paths. To create a smooth transition between a network of paths and a bridge they should be coordinated and modified where necessary.

The following values are stipulated:

- Maximum ramp gradient 6%
- Minimum useful flight width between edge deflectors 120 cm (suitable for wheelchair users)
- For ramps longer than 600 cm an intermediate landing 150 cm in length is required

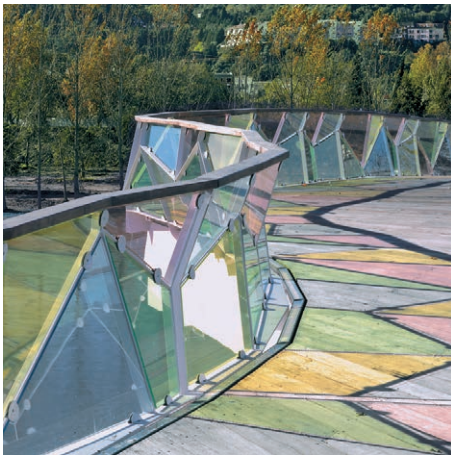


15

- Minimum dimensions of stairs
  - single-flight stairs
  - stairs with a landing
  - Laurin stairs
- Minimum dimensions of lifts
- Stairs and lift, Bridge for Deutsche Telekom, Bonn (D) 2010, schlaich bergemann und partner
- Stairs and lift, Salinensteg, Bad Rappenau (D) 2008, schlaich bergemann und partner
- Dimensions of ramps with the maximum permitted gradient of 6% and an intermediate landing with a maximum length of 6 m
- Required vertical width DB of covering band
- Ramps and landings, Römersteinbruch, St. Margarethen (A) 2008, AllesWirdGut; Gmeiner-Haferl



16



17



18



19

- 10 cm high edge deflectors
- Handrails on both sides at a height of 85 cm above the deck surface
- at the beginning and end of the ramp free space of 150 x 150 cm

Intermediate landings on ramps longer than 600 cm prevent people using the ramp from tiring quickly. These intermediate landings result in the walking surface looking bent and reduce average gradient  $s_m$  from 6 to 5.3% (Fig. 13, p. 13). This is determined by the following formula:

$$s_m = \frac{s_1 \cdot l_1 + s_2 \cdot l_2 + s_1 \cdot l_1}{l_1 + l_2 + l_1} [\%]$$

$s_m$  average gradient [%]  
 $l$  length [m]

This means that the ramp must be extended by a further 13%. This bent surface can be concealed by installing a cordon, which results in a continuous view. The required vertical width  $\Delta B$  of the cordon can be determined using the following formula (Fig. 14, p. 13):

$$\Delta B = (s_m - s_2) \cdot L_2 = (-s_m + s_1) \cdot L_1 [m]$$

### Railings

Various demands are made on pedestrian bridge railings. On the one hand they serve to protect people from falling off the bridge, so they must be able to withstand horizontal loads of up to 0.8 kN/m. On the other hand they are designed to offer support and guidance, especially for people whose mobility is impaired. The prescribed height of handrails for pedestrians is 1.00–1.10 m and for cyclists 1.20 m. The Forschungsgesellschaft für Straßen- und Verkehrswesen e.V. (Road and Transportation Research Association) in Cologne actually recommends a height of 1.30 m for cycle traffic

facilities. If there are railings at that height it will be useful to also install a separate handrail at an appropriate height of approximately 85 cm (Fig. 16). The “Additional technical terms of contract and guidelines for civil engineering works” (»Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten« – ZTV-ING) prescribe not only the height of railings but also provide precise specifications on the dimensions of posts and handrails and the distances between them (Figs. 20 and 21).

These very conservative guidelines apply to road traffic bridges as well as to pedestrian bridges, so they should serve only as a guide for relevant safety aspects and not as rules for construction. They would otherwise make filigree railings, which can greatly contribute to a pedestrian bridge’s transparency, impossible.

Railing infill must be installed so that there is no danger of people – especially small children – slipping through them or climbing on them. Flat, closed elements (Fig. 17) or relieved elements can be installed to avoid this danger (Figs. 16, 18 and 19). Horizontal or vertical rods and wire or cable nets prevent people from slipping through open infill. For railings with vertical infill rods, the maximum distance between the rods should be 12 cm. People must be prevented from climbing on or over horizontal infill rods by inward sloping railings or handrails (see Finishing, p. 68ff.). Choosing a narrow-gauge mesh with a maximum of 60 x 40 mm for cable net railings will prevent people from climbing on it.

### Surface

A pedestrian bridge’s surface has many functions. It provides the necessary slip-resistance as well as a continuous final finish to the pedestrian deck. The sur-

face also seals the bridge's transverse section, minimising corrosion and protecting the structure from mechanical damage.

No slip resistance specifications are provided in bridge construction regulations. BGR 181 issued by the "Berufsgenossenschaft Handel und Warendistribution" ("Retail and Goods Distribution Liability and Insurance Association") is helpful here. It outlines five categories specifying degrees of slip resistance. Surfaces in the R9 category must comply with the lowest and those in category R13 must comply with the highest degrees of slip

resistance. A slip resistance in category R10 or R11 is prescribed for outdoor walkways. This degree of slip resistance can be easily achieved by installing bituminous or mineral surfaces. Bituminous surfaces are tried and tested, but have the disadvantage of also being very thick (60–100 mm) and thus very heavy. So-called 'thin film surfaces' made of epoxy resins can be used as an alternative. These are 5 to 10 mm thick and are interspersed with quartz sand to form a surface. They can be laid on concrete and steel, so they are particularly suitable for the construction of pedestrian bridges.

Wood, glass or grid surfaces can also be load-bearing elements, however, they may have to be adapted to local single loads, such as for the wheel load of a light commercial vehicle. These surfaces require additional slip resistance measures when they are wet. More slip-resistant wood surfaces can be created by grooving the wood or installing epoxy resin strips with a sand finish. Glass can be made more slip-resistant by etching or sandblasting the surface. The slip resistance of grid surfaces can be improved by profiling the grid bars (see Finishing, p. 65ff.).

**Minimum dimensions for steel railings**

Railing height	<ul style="list-style-type: none"> <li>at a fall height of &lt; 12 m</li> <li>at a fall height of &gt; 12 m</li> <li>for cycle paths and pedestrian and cycle paths</li> </ul>	<ul style="list-style-type: none"> <li>≥ 1000 mm</li> <li>≥ 1100 mm</li> <li>≥ 1200 mm</li> </ul>
Post positioning	<ul style="list-style-type: none"> <li>for infill rods and cross-beam railings and railings with wire netting infill</li> <li>for short-post filled-rod railings</li> <li>for tubular railings</li> <li>for vertical extension rails</li> </ul>	<ul style="list-style-type: none"> <li>2000–2500 mm</li> <li>≤ 2000 mm</li> <li>1500–2000 mm</li> <li>2670 mm</li> </ul>
Handrail width	<ul style="list-style-type: none"> <li>for bridges over roads and paths</li> <li>for pedestrian and cycle path bridges</li> <li>for tubular railings and service roads</li> <li>Clearance of infill rods</li> </ul>	<ul style="list-style-type: none"> <li>≥ 120 mm</li> <li>≥ 80 mm</li> <li>≥ 60.3 mm</li> <li>≤ 120 mm</li> </ul>
Clearance between bases and ledges	<ul style="list-style-type: none"> <li>for short-post filled-rod railings</li> <li>for railings with wire netting infill</li> </ul>	<ul style="list-style-type: none"> <li>120 mm</li> <li>80 mm</li> <li>50 mm</li> </ul>
Distance between the axes of the posts and the joint or end of the wing		≥ 250 mm
20 Projection of the handrail (lower section) above end posts		50 mm

Structural element	Profile [mm]	
	Cold profiles	Tubes
Handrail, not shared	120/28/27, 5/23/65/23/27, 5/28 × 4 or equivalent or 80/30/17, 5/12/45/12/17, 5/30 × 4 for pedestrian and cycle path bridges	60.3 × 2.9
Handrail shared		
• Upper section	18/25/120/25/18 × 4	
• Lower section	15/50/80/50/15 × 4	
Cross beam	60 × 40 × 4	60.3 × 2.9
Posts	70 × 70 × 5	60.3 × 2.9
Short posts	60 × 60	
21 Infill rods	15 × 30	

- 16 Filled-rod railing
- 17 Railing made of glass plates set at different angles
- 18 Railing made of woven steel
- 19 Steel mesh railing
- 20 Minimum dimensions for steel railings in compliance with ZTV-ING, Part 8
- 21 Cross-sections and thicknesses for steel railings in compliance with ZTV-ING, Part 8

**Note**  
[1] RWTH Aachen et al. Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008



## Statics and dynamics

Pedestrian bridges must be designed to be both static and dynamic. To test their stability, various impacts are simulated and a static calculation is used to determine the bridge's dimensions and behaviour.

### Statics

Static loads for pedestrian bridges are prescribed in individual countries' regulations. In Germany it is the DIN Technical Report 101 "Impacts on bridges" (DIN-Fachbericht 101 »Einwirkungen auf Brücken«), that specifies the load of a bridge's own weight as well as traffic loads, wind, temperature, impact and snow loads. European standardisation means that Eurocodes are due to replace the DIN technical report but they will adopt the technical report's main approaches, so no fundamental changes are expected.

### Vertical loads

A bridge's own weight and traffic loads are the main vertical loads. Wind and snow loads are less important.

### Traffic loads

The vertical traffic load on a pedestrian bridge is estimated at 5 kN/m<sup>2</sup> for bridges with spans of up to 10 m. Loads are lower for bridges with wider spans in accordance with the following formula:

$$2.5 \leq q_{fk} = 2.0 + \frac{120}{l_{sj} + 30} \leq 5.0 \text{ [kN/m}^2\text{]}$$

$l_{sj}$  Individual span [m]  
 $q_{fk}$  Distributed area load [kN/m]

This reduces traffic area loads for 25 m spans to 4.18 kN/m<sup>2</sup>, for 50 m spans to 3.50 kN/m<sup>2</sup> and for 100 m spans to 2.92 kN/m<sup>2</sup>.

Figure 1 makes it clear that the maximum load per m<sup>2</sup> is only reached with very

large crowds of people. Even dense pedestrian traffic usually consists of just 1.5 persons/m<sup>2</sup>, which is a traffic load of 1.20 kN/m<sup>2</sup>, not even a quarter of the estimated maximum load. It is advisable to estimate the probability of such unusual crowding in advance and from this to derive a more nuanced and realistic assessment of the maximum load, which can also result in lower dimensions and costs. The usual standards (Fig. 2, p. 18) do not allow for any differentiation in this area, so a little-used bridge for hikers must be designed to have the same distributed area load as an access bridge for an event hall.

A more differentiated approach would also be appropriate in determining load distributions in a lateral direction. It is highly unlikely that a crowd of panicked people would be on just one side of a bridge with nobody on the other side. DIN Technical Report 101, however, only allows for a more differentiated consideration of loads for bridges with a deck width of 6 m and over. Yet even for narrower bridges a differentiation between loads on the two sides of just 50% would certainly be more realistic and given the torsional stress that often determines a bridge's dimensions, which would also be reduced by 50%, would result in major savings on the cross section (Fig. 3, p. 18).

Two approaches can be used in the local analysis of individual structural components: either an individual load of 10 kN can be taken into account or if emergency or service vehicles drive on it, the bridge's load can be calculated with a load model based on a 2-axle light truck with a total weight of 12 t (120 kN) (Fig. 4, p. 18). For secondary structural components in particular (e.g. cross girders), such a model can be relevant to the bridge's overall measurements.

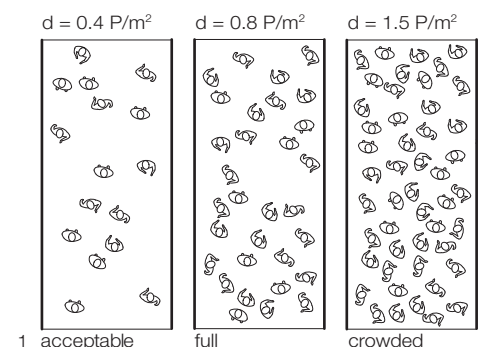
### Horizontal loads

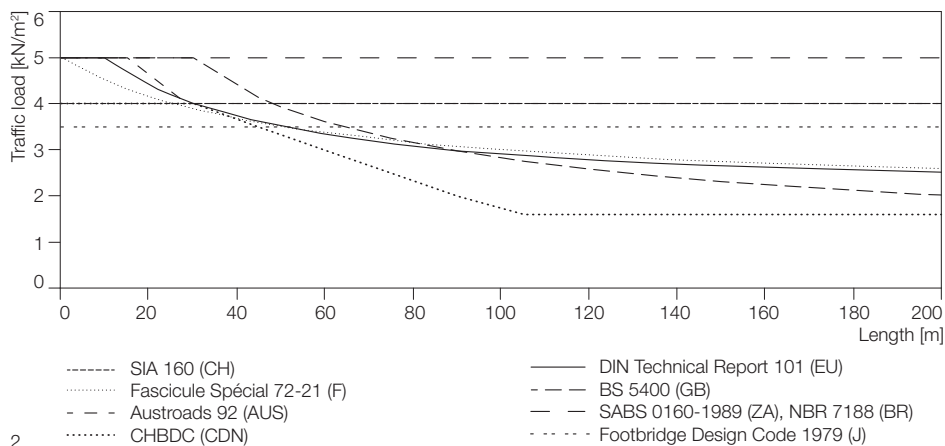
Pedestrian bridges often have a very low width to length ratio, so horizontal transverse loads can influence their dimensions, especially if they have broad spans. In contrast, horizontal longitudinal forces play a subordinate role.

### Traffic loads

Horizontal traffic loads with a longitudinal direction are estimated across the board at 10% of the vertical distributed area load and with the addition of vehicle loads at 60% of the bridge's own vertical load.

Railings must also be designed to take horizontal loads, which will determine the dimensions of balusters and their anchoring in the superstructure. Horizontal loads are usually bypassed in the support system, so that no loads from the bridge deck affect the support columns or abutment. The beam load on the hand-rail, directed either outwards or inwards, is set at 0.80 kN/m.





2

**Impact load**

DIN Technical Report 101 specifies a horizontal impact load for structural components exposed to danger of 1,000 kN in the traffic direction and 500 kN at a right angle to the traffic direction at an impact height of 1.25 m (for bridges over roads). These loads are declared exceptional impacts and may therefore be subject to lower safety levels. They are however so large that they basically preclude slender support pillars. If these are still desired, it must be proven that their stability will be ensured, even if the pillars fail or become very deformed. Otherwise, the only solution is to build thick support pillars, a massive, impact-resistant base or a robust protective or deflective structure.

**Wind loads**

Another component that often determines a bridge's dimensions, and for bridges with broad spans sometimes also its design, is wind load. Appendix N of DIN Technical Report 101 contains wind load specifications. Wind speeds depend on a bridge's location (wind load zone) and height. A bridge's cross-sectional shape also influences the wind load on its structure. The wind load resulting from wind flow around a bridge is determined by the aerodynamic shape parameter  $c_p$  and by its surface area.

Fig. 6 shows the values for wind loads on some common bridge cross sections in zones 3 and 4. If there are pedestrians or cyclists on the bridge, the cross section the wind is flowing around changes accordingly. This can be accounted for in the design with a rectangular traffic platform built at a height of 1.80 m. The wind load  $W$  can range from 0.8 kN/m<sup>2</sup> for slender piers close to the ground in wind load zone 1 up to 4.7 kN/m<sup>2</sup> for very high, compact superstructures near windy coasts (wind load zone 4). Com-

mon types of cross sections can be exposed to wind loads ranging from 1.0 to 3.0 kN per metre.

Measurements made on many bridges have shown that the loads specified in the standard are set mainly higher than the values measured. Since the standard makes only generalised statements, it is often more useful to identify more realistic wind loads with a wind tunnel test. In these tests, a model of the structure built to scale with appropriate pressure sensors is placed in a wind tunnel and exposed to a turbulence flow similar to that of flows expected at the structure's site (Fig. 5).

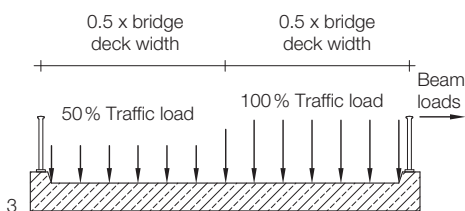
It is well worth using wind tunnel tests to realistically assess loads, especially when building large bridges, so that the structures can be designed to be more efficient and profitable. The costs of testing will be more than offset by the savings made on materials and optimised cross sections.

Light pedestrian bridges are also often susceptible to vibration. This form of excitation by wind can easily be tested in a wind tunnel.

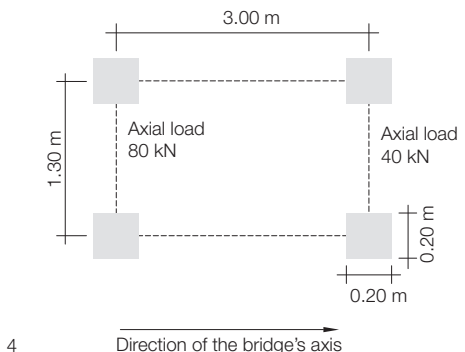
**Temperature loads**

Temperature loads may become important if they cause deformation and affect a structure's fitness for purpose. A temperature change of 30 °C can cause a stressed ribbon bridge with a 100 m span and a 2 m ribbon sag to warp in mid-span by approx. 30 cm – a considerable magnitude.

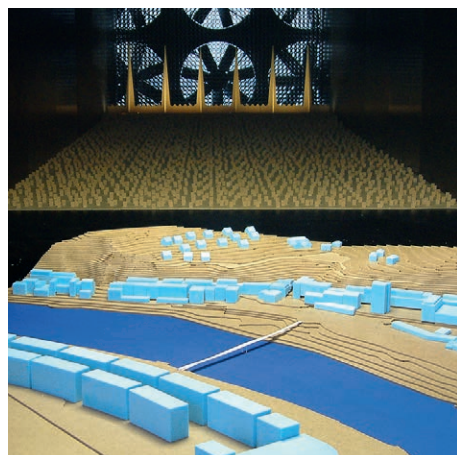
Substantial forces can be induced if expansions or contractions due to temperature changes are obstructed in statically-indeterminate structures. Integral bridges having no bearings can only react to changes in the superstructure's length with increased secondary stress. Chapter V of DIN Technical Report 101



3



4



5

Effect of wind W [kN/m <sup>2</sup> ] without traffic				Effect of wind W [kN/m <sup>2</sup> ] with traffic		
on superstructures						
b/d	$z_e \leq 20$ m	$20 \text{ m} < z_e \leq 50$ m	$50 \text{ m} < z_e \leq 100$ m	$z_e \leq 20$ m	$20 \text{ m} < z_e \leq 50$ m	$50 \text{ m} < z_e \leq 100$ m
$\leq 0.5$	2.55	3.55	4.20	2.10	2.95	3.45
$= 4$	1.40	1.95	2.25	1.15	1.60	1.90
$\geq 5$	1.40	1.95	2.25	0.90	1.25	1.45
on pillars and piers <sup>1</sup>						
b/d	$z_e \leq 20$ m	$20 \text{ m} < z_e \leq 50$ m	$50 \text{ m} < z_e \leq 100$ m			
$\leq 0.5$	2.40	3.40	4.00			
$\geq 5$	1.05	1.50	1.75			

<sup>1</sup> Wind effects on piers and pillars can be reduced by 50% by using square piers or piers with square cross-sections with curved corners with a ratio of  $r/d \geq 0.20$ ,  $r$  is the radius of the curve.

defines the temperature loads that combine in a cross section made of various components (Fig. 7, p. 20). Even temperature changes (Fig. 7a) and the linear variable temperature rate (Figs. 7b and c) are usually estimated for bridges. Temperature changes in structural components can range from 35 to +40 K. The linear variable temperatures in the cross section can range from +18 to -18 K. Adverse stresses can also be caused by temperature differences between different structural elements (e.g. tension member and arch or hanger/cable stays and superstructure). As well as a constant rate for all structural components, 15 K must be taken into account as a possible differential.

#### Vandalism

Vandalism is often discussed, although its impact is less of a load than a case of destructive activities and a related failure of individual structural components modifying the static system and reducing the bridge's load-bearing capacity. A risk assessment should be able to realistically assess the probability of vandalism and its effects on a structure's safety, ensuring that no excessive demands will have a significant effect.

#### Dynamics

Pedestrian bridge vibration is an important but often neglected topic. Excessive vibration can greatly impair a bridge's fitness for purpose and disturb pedestrians. Various effects can make a bridge vibrate, especially if it is very flexible and has a light cross section or broad spans. Two dynamic excitations are especially significant:

- human-induced vibrations, including deliberate excitation or vandalism (if people make a bridge vibrate excessively by rhythmical jumping, knee bends or rocking).

- wind-induced vibration, such as turbulence-induced transverse vibration and aeroelastic instability (e.g. flutter or galloping, see p. 22)

Fluctuations in air pressure caused by passing vehicles can also make pedestrian bridges crossing just above roads or railway lines vibrate.

The issue of vibration in pedestrian bridges is as old as bridge construction itself. Historic suspension bridges, such as the Saint Georges bridge over the Saône in Lyon show, however, that vibration does not automatically cause problems. This footbridge connects two Lyon suburbs and many people walk across it every day. Its vibrations can be clearly felt but do not affect pedestrians. Many of these suspension bridges remain in use for several decades and none is known to have collapsed due to fatigue or vandalism.

On the other hand, prominent examples such as the Millennium Bridge in London and the Passerelle Solférino in the centre of Paris, show that excessive vibration can greatly impair a bridge's fitness for purpose if the vibrations are strong enough to make it hard for users to walk or to substantially decrease their comfort.

Both bridges attracted negative publicity. The Millennium Bridge was in particular subject to horizontal vibration, which is especially uncomfortable for pedestrians. In both cases, the bridges were expensively refurbished and additional damper elements were installed after completion (Fig. 8, p. 20). This is something of a balancing act, because on the one hand, dampers and tuned mass dampers should be avoided for economic and often for design reasons, but on the other hand a bridge cannot be allowed to move unpleasantly or accelerate such

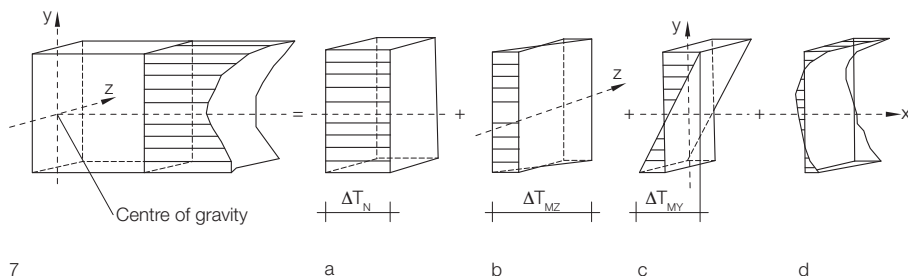
that it negatively affect its users.

Two approaches to controlling pedestrian bridges' dynamic behaviour are therefore taken in their design:

- Avoidance of wind-induced vibration and in particular aeroelastic instability due to wind
- Avoidance of excessive vibration and the resulting restriction of the bridge's fitness for purpose due to human-induced vibrations

Potential vibration problems should be dealt with at an early stage in the pedestrian bridge's design when they can still be responded to appropriately. During the design process, when there is still no precise data available on footing, damping, final cross sections and any pre-load forces in the support cables, pre-static calculations should also be made to identify the bridge's natural frequencies and normal modes. These calculations can provide a wealth of information on a structure's expected vibration behaviour, allowing planners to react to possible excessive vibrations in the design phase and to easily incorporate counter-measures. Extra dampers can, for example, be optimally integrated into the design and any necessary anchoring or reinforcement provided.

- 1 Various pedestrian traffic densities
- 2 Traffic loads for pedestrian bridges in various countries according to span length
- 3 Differentiated treatment of loads in the event of unilateral traffic loads
- 4 Point loads of a light truck as load model for calculating individual structural elements subject to exceptional loads
- 5 Wind tunnel test for a pedestrian bridge in Lyon with turbulence field and wind rotors
- 6 Wind effects on bridges for the wind load zones 3 and 4 (inland)
  - b Bridge deck width [m]
  - d Top edge height including parapet if any to lower edge of the support structure [m]
  - $z_e$  Wind-resulting



7

As the two examples mentioned above show, it is possible to subsequently improve the vibration behaviour of a completed bridge through measures such as the installation of dampers. Dampers do not however always fit optimally into a design and can tend to look like extraneous elements.

Experience gained systematically in recent years in the area of human-induced vibration and research into the synchronisation of pedestrians with lateral vibrations have helped to make it possible to calculate excessive vibration in advance and thus avoid it. The EU-funded SYNPEX and HIVOSS [1] research projects and the French road construction authority SETRA have developed new methods of measuring human-induced vibration that planning engineers can easily use. These make it easy to estimate expected accelerations and compare them with the limits stipulated in the comfort classes.

Wind engineers, who can carry out wind tunnel tests if necessary, should be consulted on designs likely to be subject to wind-induced vibration and aeroelastic instability.

#### Natural frequencies and normal modes

A pedestrian bridge, like every structure, is a system capable of vibration. If a bridge is briefly excited by an impact to its deck, for example, it vibrates for a certain period at a certain natural frequency, so this is a major key figure in assessing its susceptibility to vibration. The natural frequency of a beam bridge for example, depends mainly on its span length, bending stiffness and the mass of the bridge's deck.

The greater the bridge's bending stiffness, the higher its natural frequency will be. The longer or heavier the bridge, the lower its natural frequency. Every pedestrian bridge has its own vibration pattern.

Like a guitar string, but much slower, it has fundamental frequencies and harmonics, which are also called natural modes. These are consecutively numbered according to their oscillation periods, with the longest oscillation period referred to as the first normal mode. Normal mode is also referred to as mode shape. It describes the bridge in a deflected state, like a pendulum at maximum deflection.

Normal modes can be used to differentiate vertical and horizontal bending vibrations as well as torsional or rotational vibrations, of a beam bridge for example (Fig. 10). The cables of suspension bridges mean that coupled normal modes combining torsional and bending vibrations can often occur in this type of bridge (Fig. 11).

Simple bridges' natural frequencies can be identified by means of tables or pen-and-paper calculations. The natural frequencies and normal modes of more complex load-bearing systems, such as suspension bridges, support structures trussed with sag rods or curved bridges, can be calculated by using the Finite Element Method (FEM). This calculation method is now used in the design phase for preliminary calculations, allowing an initial assessment of the bridge's expected behaviour to be made at a very early stage. In calculating natural frequencies, it must be noted that all additional loads such as the surfacing, deck structure and railings and their masses must also be taken into account. This additional mass leads to a lowering of natural frequencies. A 20% increase in the mass of a beam bridge means a 10% increase in the bridge's vibration period or, to put it another way, a 10% reduction in its natural frequency. For light bridges, where the ratio between the bridge deck mass and the mass of pedestrians is low (ratio bridge/people



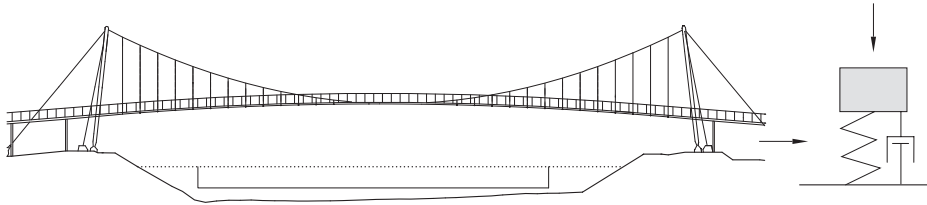
8

< 0.8), the additional mass of pedestrians in a continuous stream of pedestrians should be taken into account, because this further lowers the natural frequency. The mass of individual people or groups of up to ten people can however generally be safely neglected.

The modal mass of every normal mode can also be calculated. FEM programmes often display this value in the eigenvalue calculation. It shows which mass is active in a vibration. It is not hard to transfer the vibration problem from the complex calculation model in the FEM programme to an easily calculable single mass oscillator. This makes it possible to carry out the calculation with a concentrated mass, which is positioned on a spring with the same vibration period as the bridge (Fig. 9).

#### Excitation, system response, resonance

Dynamic excitations include loads that change their position or size with varying speed (e.g. pedestrians), and sudden loads, such as those caused by wind gusts. The bridge, and especially the bridge deck, responds with an elastic deformation, depending on the load. Observing deformation changes over a period of time will reveal the speeds and accelerations, which can be used to assess the pedestrian bridge's comfort. A bridge's ability to vibrate will only become a problem in the presence of a relevant excitation. If there is a great disparity between a pedestrian bridge's excitation frequency and its natural frequency, any vibration will be barely perceptible. If however, dynamic excitation frequencies correspond with the bridge's natural frequency, resonance, i.e. an amplified resonance response from the system, will occur. This greatly increases the maximum system response to a dynamic load, even under the same static load. Resonance occurs



9

when accelerations result from the ratio of the excitation to the vibrating mass and to damping. The greater the damping or vibrating mass, the smaller the accelerations, i.e. given the same excitation but double the mass, the accelerations will be only half.

**Damping**

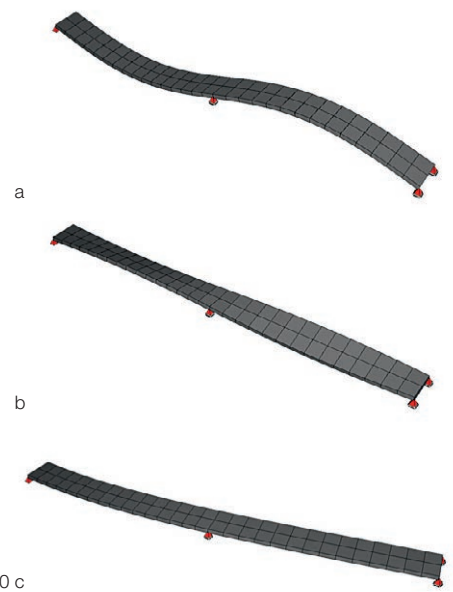
Damping deflects the vibrations, reducing their amplitude and the vibrations subside. The vibrating system's kinetic energy is dissipated, i.e. converted into other forms of energy, such as heat. There are various kinds of damping. Structural damping describes the damping behaviour of a structure, with its joints and supports, while material damping describes only inner damping in the elements due to varying loads. It is hard to reliably and realistically estimate damping values in planning because many factors influence damping behaviour. Damping may be modified by different means of joining, depending on whether joints are screwed or welded together, for example. Experience has shown that fittings such as an asphalt surface and a wire mesh railing can greatly contribute to damping, which can be proven by subsequently measuring the damping.

**Excitation by wind**

Wind can also make bridges vibrate. This can result in excessive loads, although less from vibrations caused by wind gusts than from turbulence-induced transverse vibrations and aeroelastic instability. Aeroelastic instability includes phenomena such as bending and torsional galloping, flutter and divergence. While aerodynamics deal with aerodynamic forces, aeroelastics describes the often very extensive interactions between a support structure's elastic behaviour and aerodynamic forces.

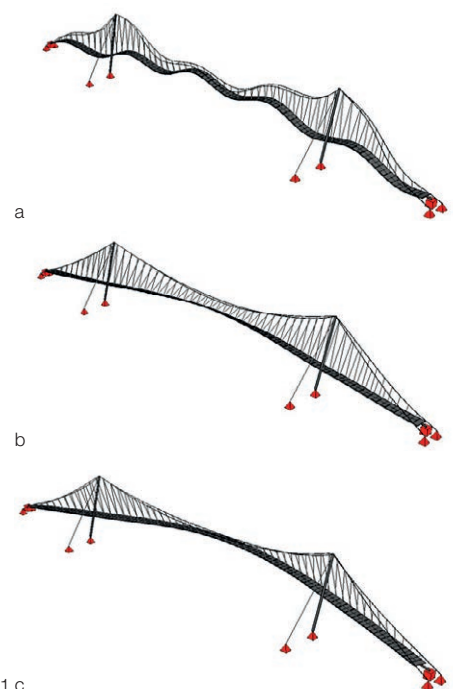
Unstable behaviour means that a system is no longer in equilibrium. Aeroelastic instability occurs when both forces increase due to an amplifying interaction between aerodynamic forces and vibrations. More energy is fed into the vibrating system than the structural damping and aerodynamic damping can dissipate, so the system vibrates at ever-increasing amplitudes.

*Turbulence-induced transverse vibrations*  
Turbulence-induced transverse vibrations are caused by the periodic impact of turbulence on a cross section. If the frequency of turbulence corresponds with the bridge's natural frequency, resonance with large amplitude vibrations occurs. Targeted damping measures can however limit these amplitudes.

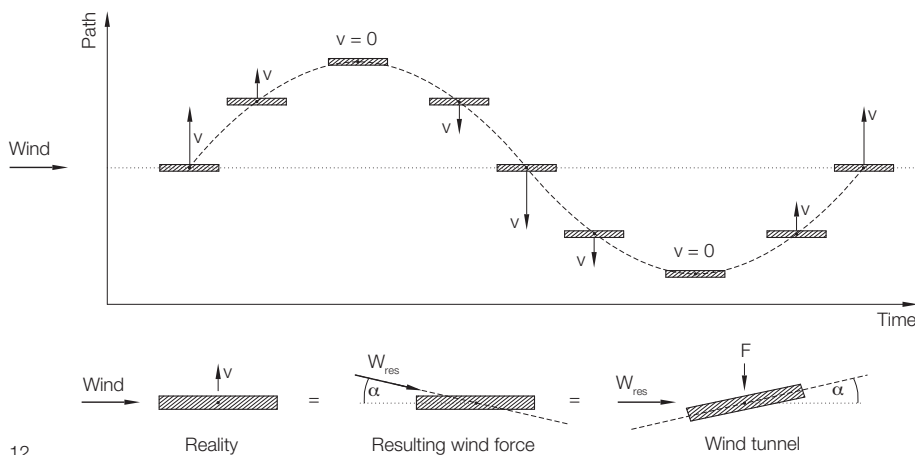


10 c

- 7 Temperature curve for a single structural element
  - a Even changes in temperature  $\Delta T_N$
  - b Linear variable temperature rate at the x-z level  $\Delta T_{Mz}$
  - c Linear variable temperature rate at the x-y level  $\Delta T_{My}$
  - d non-linear temperature distribution  $\Delta T_E$
- 8 Dampers, Millennium Bridge, London, (GB) 2000, Foster + Partners, Sir Anthony Caro; Ove Arup & Partners
- 9 A suspension bridge's vibrations can be transferred to an easily calculable single mass oscillator.
- 10 Normal modes of a beam bridge
  - a Vertical flexural vibration
  - b Torsional vibration
  - c Transversal vibration
- 11 Normal modes of a suspension bridge,
  - a Vertical flexural vibration
  - b Torsional vibration
  - c Transversal vibration



11 c



12

### Galloping

Galloping is an aeroelastic instability typical of slender structures, occurring, for example, when icicles form on high-voltage power lines as well as in light pedestrian bridges or those with long spans. The vibrations in galloping are caused by the cross section's own movement in the wind (Fig. 12) so that the bridge executes bending or torsional vibrations. This can easily be simulated in a wind tunnel in a static test by measuring wind force from various angles and ensuring that the change of wind force  $\Delta F$  does not become negative so no forces increase the movement (Fig. 13). The amplitudes that occur can be several times higher than the cross section. To avoid this effect, the speed at which galloping starts should always be greater than the maximum expected wind speed. If there is little disparity between the critical speed for turbulence-induced transverse vibrations and the speed at which galloping is initiated, interaction effects between turbulence-induced transverse vibrations and galloping can occur. In this case, aeroelastic wind tunnel tests should be carried out.

### Flutter

Flutter is an aeroelastic phenomenon in which vertical and torsional vibrations are coupled and wind flows cause variable forces to impact the cross section, further amplifying the vibrations. These are also self-induced vibrations, in which movement in the wind leads to a further increase in the load. The system draws energy from the flow and stores it in the form of elastic deformations. A small initial deflection, such as a gust of wind, can initiate this mechanism. If energy input into the bridge becomes greater than the energy dissipated by damping, vibration will greatly increase. A famous example of the destructive effect of this

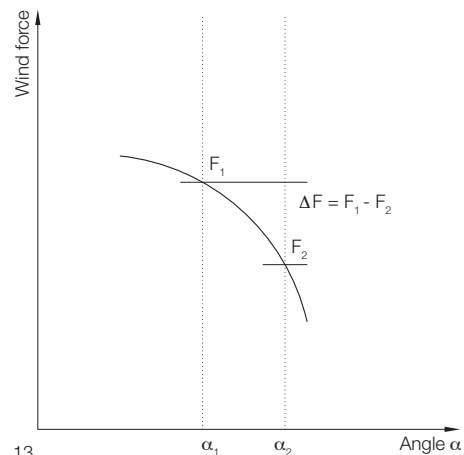
phenomenon is the Tacoma Narrows Bridge in the American state of Washington, which collapsed in 1940 after just four months in operation.

Flutter occurs in particular with deformable, slab-shaped cross sections, which bridge decks often are. DIN 10554 on »Wind loads« provides simple tips on the conditions in which there is no danger of flutter occurring:

- The bridge deck should have an elongated cross section with a width ( $d$ ) to height ( $b$ ) ratio of  $d/b > 4$ .
- The bridge deck's axis of torsion must be parallel to the deck and at a right angle to the prevailing wind direction. A certain distance ( $d/4$ ) must also be maintained between the centre of movement and the edge of the cross section facing the wind. The cross sections of bridges whose centres of movement usually lie in the middle of the bridge generally fulfil this requirement.
- The bridge's lowest natural frequency must be part of a torsional vibration or torsional natural frequency that is approximately double that of the lowest flexural natural frequency. This means that rotation movement's frequency must not be allowed to coincide with the frequency of a vertical vibration and that they must be at a sufficient distance from one another.

### Divergence

Another aeroelastic phenomenon is divergence. This is however not a dynamic problem that occurs in the context of vibration but a static problem. Wind forces often produce a torsional moment on a bridge's cross section, causing it to rotate more with increasing wind speed. This imposes a higher torsion load, which in turn results in increased deformation. The structure will be stable as long as its



13

stiffness prevents the increase in rotation from becoming greater than the increase in the load caused by rotation.

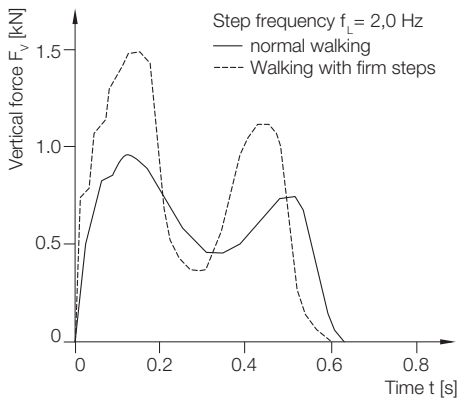
In most cases, the critical wind speed at which divergence occurs is higher than that for flutter, so this phenomenon is of secondary importance.

Every bridge design should aim to avoid aeroelastic instability. In contrast to human-induced vibrations, which can be controlled using dampers, thereby complying with the maximum values, experience has shown that problems associated with aeroelastic instability cannot be solved by increasing damping. Sound aerodynamic design of the cross section, such as the attaching of deflector plates to the side of the bridge deck, which reduces the impact of air flows on the cross section, can prevent aeroelastic instability. Wind tunnel tests are usually essential to a bridge's design and in proving the effectiveness of deflector plates. These tests are carried out on a model representing a section of the bridge's cross section that is mounted on springs so it can be adjusted to ensure that the model's dynamic behaviour is consistent with the real bridge's.

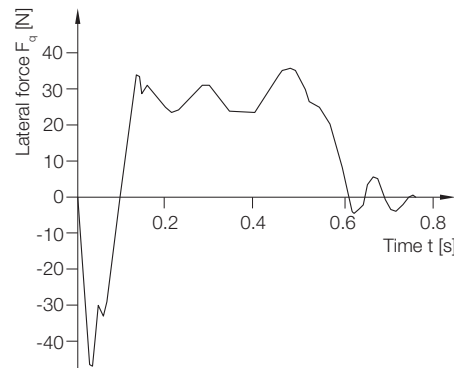
### Excitation by pedestrians

Pedestrians move at various speeds and have different step lengths and step frequencies. Average normal walking step frequency is 1.8–2.0 Hz, with the lower limit at about 1.3 Hz and the upper limit at approx. 2.3 Hz (Fig. 15). These two figures mark the critical area in which the bridge can be excited to cause vertical or torsional vibrations. Simplified assumptions made in the design may not hold in reality, so forces impacting the bridge may fluctuate.

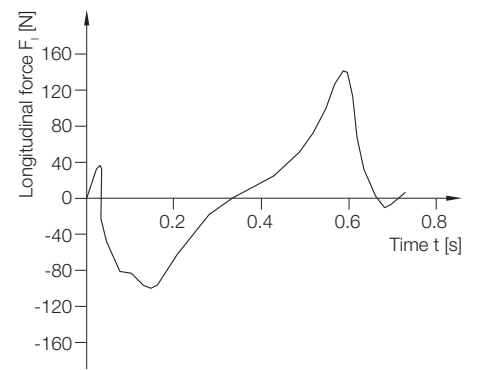
Individual pedestrians or groups can cause a bridge to vibrate in vertical and horizontal directions. Every step imposes a pulse-like load on the bridge; many



14 a



b



c

steps can lead to excitation with a consistent rhythm. Every step results in a force component in a vertical direction (vertical force  $F_v$ ) as well as a lateral (lateral force  $F_q$ ) and a longitudinal component (longitudinal force  $F_l$ ) with respect to the traffic direction and thereby excites the pedestrian bridge to vertical or torsional vibrations or lateral oscillation (Figs. 14 and 16, p. 24). This especially effects natural frequencies in the range of the step frequency of pedestrians.

One phenomenon that was already well known when the Millennium Bridge in London was built, is that of horizontal vibration increasing to greater amplitudes. This occurs because the deck's swaying leads pedestrians to change their gait and adopt a kind of "sailor's walk", which exerts a much greater transversal force than normal walking. If pedestrians try to move at the same frequency as the swaying, the problem is magnified due to resonance. This is referred to as the synchronisation of pedestrians with a bridge or "lock-in effect". After its problems with the Millennium Bridge, the Arup firm carried out comprehensive investigations and summarised their results in universal design proposals for testing for the risk of the lateral lock-in effect.

Pedestrian bridges can and should move when pedestrians use them and this must not always be only regarded as disturbing. Swinging footbridges can be fun, but they must also always be fit for purpose.

In some older regulations and standards, natural frequencies of more than 5 Hz in pedestrian bridges were recommended or called for so as to completely avoid human-induced vibrations. This frequency criteria would unnecessarily restrict design diversity. Light pedestrian bridges with long spans such as suspension or

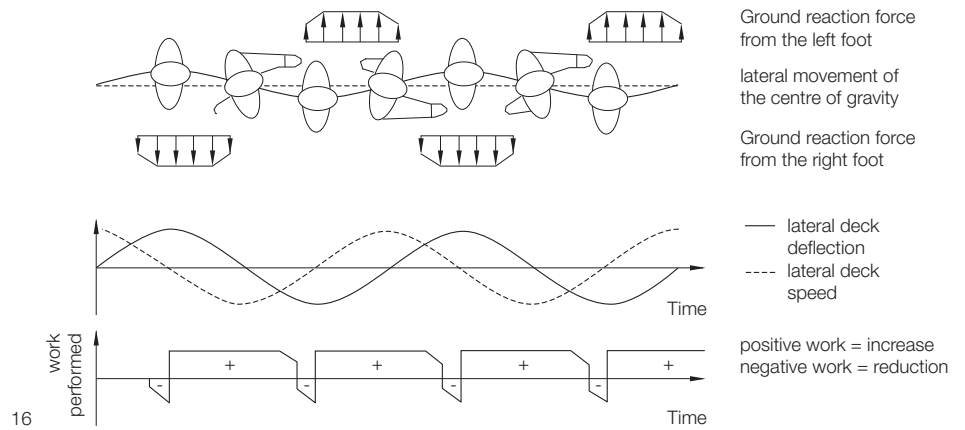
stress ribbon bridges could not be built in compliance with this specification and designs with long spans would not be economically viable. For this reason, the SYNPEX and HIVOSS research projects developed a new method for calculating the natural frequencies of pedestrian bridges in the range of pedestrians' step frequencies. It recommends the following steps:

- Calculation of the bridge's natural frequencies
- Testing whether the system's natural frequencies are in the critical range. 0.5–1.2 Hz is regarded as critical for lateral oscillation, while 1.25–2.30 Hz is seen as critical for vertical and torsional vibrations. Natural frequencies ranging from 2.5 to 4.6 Hz could also cause vertical and torsional vibrations, although no cases of this range of frequencies leading to excessive movement are known.
- Selection of design situation, which consists of traffic density and a comfort criterion. The comfort criterion corresponds with a maximum acceleration of the walking surface. The probability and frequency of various impacts must also be taken into account in choosing the design situation.
- Estimate of the damping necessary for the design
- Calculation of the speed of the specified traffic density. The corresponding load models have a constant vibration pattern over time, which can be found in the relevant specialist literature [2]. This calculation can be made in a modal analysis or by using FEM programmes.
- Testing for the risk of lateral "lock-in"
- Proving fitness for purpose by comparing the accelerations identified with the comfort class specifications. If the specifications are not complied with, further measures will be required.

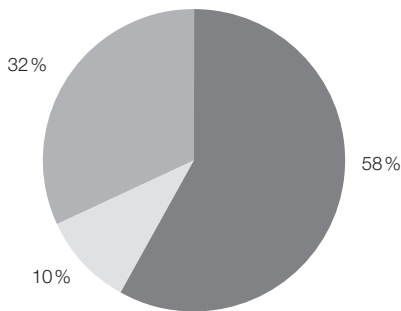
- 12 Simulation of forces  $F$  on a cross section from varying angles  $\alpha$  (galloping)
- $v$  speed of the cross section in the wind
- 13 Critical force vectors for galloping from various angles  $\alpha$
- 14 Vertical (a), lateral (b) and longitudinal forces (c) on a bridge surface caused by walking
- 15 Typical step frequency, speed and step length of an adult

	Step frequency $f_s$ [Hz]	Speed $v_s$ [m/s]	Step length $l_s$ [m]
slow walking	1.7	1.0	0.60
normal walking	2.0	1.5	0.75
fast walking	2.3	2.3	1.00
normal running	2.5	3.1	1.25
fast running	> 3.2	5.5	1.75

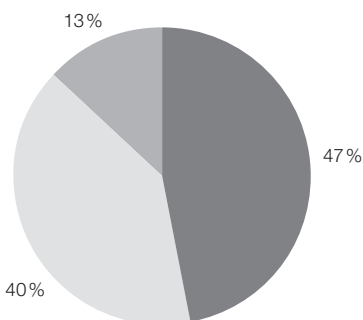
15



16



a



b

### Perception and assessment of vibrations

Perceptions of vibrations vary not only from person to person, but also depend on the vibration's frequency and direction, duration of exposure and a person's posture. Perceived vibration is an important aspect of a bridge's quality. Whether vibrations are in fact perceived as disturbing will depend on perceptions and expectations. An experiment carried out by the RWTH Aachen as part of the SYNPEX research project shows how different assessments of similar vibrations can be. The bridges studied were comparable in terms of their span length and dynamic qualities, and even the human-induced vibration speeds were similar. Only 10% of pedestrians felt that the vibrations of the decks of light suspension bridges were disturbing (Fig. 17 a), while for arched bridges the figure was 40% (Fig. 17 b). The expected vibration of the light suspension bridge is obviously greater than that of a more rigid arched bridge. When walking becomes difficult or lateral movement impairs people's balance, however it is no longer a case of subjective perception, but an objective reduction in comfort.

Important aspects in the measurement of the human-induced vibrations of pedestrian bridges are the bridge's location, traffic densities, the type of traffic and expected usage. A bridge in an urban park that people stroll over on weekends makes far fewer demands in terms of dynamic design than an inner-city bridge that links transport hubs and is crossed by thousands of commuters daily on their way to work. For this reason, traffic classes representing the relevant traffic densities were introduced into the design process. Selection of a realistic traffic class is an important basis for further planning. An engineering estimate of the frequency of various traffic densities (see Function-

al requirements, p. 9ff.) will be helpful in making decisions on the traffic density and comfort criteria relevant to the design.

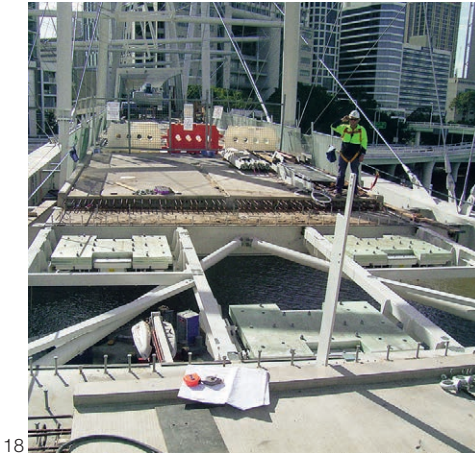
One-off or rarely occurring events, such as the bridge's opening ceremony attended by lots of people, may lead to clearly perceptible vibrations, but do not represent a static problem. In such cases, the maximum comfort class does not necessarily have to apply.

It is advisable to talk to clients at an early stage about any vibrations that may occur and point out to them that the new bridge will display certain »liveliness«. This will prepare clients and they will support the ideas behind the design of an excited, vibrating bridge.

### Measuring vibrations

On-site measurements can precisely verify the natural frequencies of bridges subject to vibration, so that damping can be calculated and the actual accelerations for small groups of pedestrians identified. These measurements can be made at comparatively little cost and effort. The measuring equipment required includes an accelerometer, a vibration meter, and an apparatus for recording the values measured. Vibration meters measure vibration speeds or accelerations. Both systems are commonly used in practice. A sufficiently large number of vibration meters on a bridge can be used to determine not only the amplitudes of vibrations but also a bridge's natural frequencies and normal modes and damping for every natural frequency. These measurements form a basis for the exact design of the dampers, whose dimensions can be determined in advance based on the calculation. After they are installed, their effectiveness should be tested with further measurements.

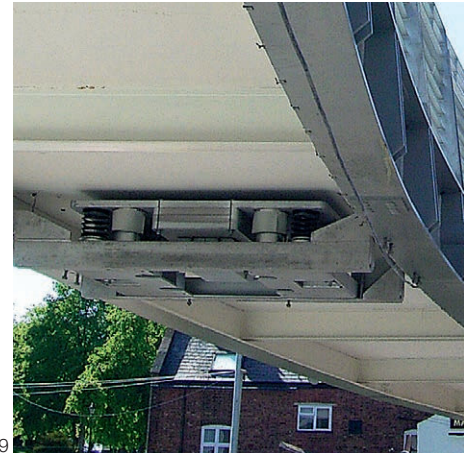
17 ■ not disturbing ■ disturbing ■ amusing



18 a



b



19

Experience has shown that structural elements such as railings and surfaces can contribute greatly to damping. Measurements of new pedestrian bridges should therefore be made only after completion, as far as possible. Sufficient time must also be planned for this and for the possible installation of damping or vibration absorption measures.

The experimental identification of specific dynamic values can be divided into two steps in accordance with the time and effort they entail:

- Step 1:  
Identification of specific dynamic values such as natural frequencies, modal shapes and damping properties. These specific values can be used to design the damping elements.
- Step 2:  
Measurement of vibrations caused by pedestrians. The goal is to test the comfort criteria and results of the calculations of the dynamic testing carried out in the design phase.

The experimental tests in step 2 should consist of several series of measurements, measuring accelerations caused by a single person, a group of people, and a flow of pedestrians. The latter involves considerable time and effort, especially for very long bridges, because it requires a large number of people. Based on these measurements, a planner can decide together with a client whether additional damping measures need to be carried out.

#### Vibration control

If the calculated or experimentally measured accelerations exceed the values in the desired comfort class, further measures will be required. The following options, among others, are available to planners:

- Changing the frequencies by modifying the bridge's mass or reinforcing it
- Increasing structure damping, e.g. by installing a damping surface.
- Installing additional damping elements
- Active vibration control, which uses devices to feed active forces into the system to counteract vibrations and reduce their amplitudes.

Changing a bridge's frequency or mass often involves an extensive and undesirable intervention in a bridge's overall design, so additive measures in the form of dampers or dynamic vibration absorbers tend to be preferred. The following damping elements, which can be installed after completion, are frequently used:

- viscous dampers
- tuned mass dampers
- tuned pendulum dampers
- tuned liquid column dampers
- liquid dampers

A very effective approach for bridges is to enhance the damping system by installing tuned mass dampers (TMD). These consist of an additional mass, a spring and a damper element, which dissipates energy by the flowing back and forth of viscous material. These three components are pre-assembled in housing then attached to the bridge. Because the TMD take up extra space, it can be advantageous to consider them during the design stage and plan the components required for their installation (Figs. 18 and 19).

Dynamic behaviour issues should be included in pedestrian bridge planning from the outset. Due to efforts in this area in recent years, these issues can now easily be predicted, assessed and corrected through damping or dynamic vibration absorption.

- 16 Schematic depiction of synchronised walking
- 17 Comparison of vibration measurements of two bridges
  - a Kochenhofsteg, Stuttgart (D)
  - b Wachtelsteg, Pforzheim (D)
- 18 Horizontal dynamic vibration absorbers (pendulum dampers)
  - a Installation of the dynamic vibration absorbers
  - b Underside of a bridge with installed dynamic vibration absorbers
- 19 Vertical dynamic vibration absorbers

#### Notes

- [1] RWTH Aachen et. al.: Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008  
RWTH Aachen et. al.: Human Induced Vibrations of Steel Structures. Leitfaden für die Bemessung von Fußgängerbrücken (HIVOSS). 2008
- [2] Heinemeyer, Christoph et. al.: Design of Lightweight Footbridges for Human Induced Vibrations. JRC Scientific and Technical Reports. 2009



## Materials



In bridge design the aim should always be to use as little material as possible. The Modernist architecture motto »Less is more« still applies. Using less material means dispensing with the superfluous and, following the principles of light-weight construction, building structures to be as light as possible and as rigid as necessary. This requires the inclusion of a range of materials. Individual materials have very different properties and their efficiency becomes especially clear in interaction with other materials. But how can a material's efficiency be evaluated?

Breaking length is a specific tensile load measurement. It describes the length at which a freely suspended cross section breaks under its own weight. With pressure loads, the maximum height is the height at which a material reaches its maximum compressive strength under its own weight. The breaking length  $L$ , and maximum height  $H$  of a constant cross section can be calculated as follows;

$$G = A \cdot \gamma \cdot L_r$$

$$P = \beta_z \cdot A$$

From  $G = P$  follows:  $L_r = \beta_z / \gamma$  or  $H = \beta_d / \gamma$ .

- G Weight
- A cross section surface [ $m^2$ ]
- $\gamma$  specific weight [ $kN/m^3$ ]
- P permissible force
- $\beta_z$  maximum tensile strength [ $N/mm^2$ ]
- $\beta_d$  maximum compressive strength [ $N/mm^2$ ]

This calculation can be applied to a suspension cable or pressure arc. If a working ratio  $f/l = 1/10$  of the length between the arch's rise or pitch and its end point is assumed, the maximum span length can be calculated by a factor of 0.8 of the breaking length or maximum height. If a suspension bridge's design is based on the realistic assumption that its cable must be capable of bearing a load equivalent to its own weight as well as its own weight, and if you include a triple safety

factor, the bridge's maximum span will be about 4,800 m. Huge bridges such as the planned Messina Bridge, which would link Italy's mainland with Sicily, could be built using conventional materials with spans approximately this maximum span size. Wider spans can only be built using glass or carbon fibre reinforced plastics, which have a much higher  $\beta/\gamma$  value (Fig. 2). Such maximum considerations are unnecessary for pedestrian bridges with their shorter spans. For light, filigree bridges however, the material's capacity and effectiveness always plays a decisive role.

### Wood

Wood rates very highly in any consideration of the efficacy of various materials as construction materials. Wood types range from soft balsa wood with a density of 1–2  $kN/m^3$  up to ironwood, with a density of more than 10  $kN/m^3$ . They differ from each other not only in strength, but in durability, which is stipulated in the

Construction material	Material tensile strength $\beta_z$ [MN/m <sup>2</sup> ]	Material weight $\gamma$ [kN/m <sup>3</sup> ]	Breaking length R [km]
High-quality construction steel	520	78	6.7
Highest quality steel cable	2,100	78	27
Spruce	80	4.7	17
Concrete	ca. 2.5	ca. 25	0.13
Glass fibre	1,500	25	60
Carbon fibre	2,100	15	140

Resistance classes				
1 very durable	2 durable	3 fairly durable	4 not very durable	5 not durable
Afzelia Maobi Billinga Greenheart Padauk Asiatic teak Makore	Oak/Sessile oak Chestnut Western red cedar Bangkirai Bubinga Merbau Bongossi Mahagony	Pitch pine	Fir Spruce Elm Northern red oak Yellow meranti	Birch Beech Ash European lime White meranti
Black locust		Pine, larch, Douglas fir		
		Yellow Cedar (Alaska cedar) American white oak		

1 Suspension bridge, Mariensteg, Wernstein (A)/Neuburg (D), 2006, Erhard Kargel

2 Tensile strength, weight and breaking length of various construction materials

3 Resistance classes of various kinds of woods

Common types of wood	Shrinkage rate			Density when kiln-dried
	axial [%]	radial [%]	tangential [%]	
<b>European softwoods</b>				
Spruce	0.2–0.4	3.6–3.7	7.9–8.5	0.43
Pine	0.2–0.4	3.7–4.0	7.7–8.3	0.49
European larch	0.1–0.3	3.4–3.8	7.8–8.5	0.55
Douglas fir	0.1–0.3	4.8–5.0	7.6–8.0	0.48
<b>European hardwoods</b>				
Oak/ Sessile oak	0.3–0.6	4.6	10.9	0.65
Chestnut	0.6	Ø 3.8	Ø 6.5	Ø 0.56
Black locust	0.1	Ø 3.9	Ø 6.3	Ø 0.72

Stress on the component	Non-critical crack depth	Non-critical crack length
Bending	< 0,7 × component height < 0,6–0,7 × component width	1/3 of the component length
Shear	< 0,7 × component height < 0,45–0,65 × component width	1/3 of the component length
Buckling	< 0,5 × component width	1/3 of the component length

4 resistance classes included in DIN EN 350-2 (Fig. 3).

The question of whether the wood will be used in the primary support structure (e.g. a truss) or in a secondary, subsidiary structural element (e.g. surface planks) will be decisive in selecting a type of wood. For small and medium spans wood can be used in a primary support structure in beam, arch and truss elements (Figs. 6 and 7). Wood can be an interesting material to use for wider spans in appropriate combinations with other materials. Joining technique plays a decisive role in wooden structural elements subject to high stress levels. Wood's tensile strength is twice as high as its compressive strength. Tensile splices are however very complicated, because forces are transferred not by contact, as with the much simpler lap splice, but must be diverted and returned through steel components (Fig. 6).

The durability of a pedestrian bridge's material is also important because these bridges are often entirely exposed to weather and varying degrees of humidity. Damage caused by weather, insects and fungus can make wood not only unsightly, but can also greatly diminish its load-bearing capacity, so it is vital to treat the wood in these structures to protect it. A basic distinction is made between the natural, structural and chemical protection of wood. Various types of wood also have their own natural protection (Fig. 3, p. 27).

Structural wood protection involves permanently protecting the material through structural measures, such as roofing (in accordance with DIN 68 800-2) so preventative chemical treatment can be dispensed with. This should generally be considered at the design stage, even if further protective measures are subsequently used.

Wood preservatives are designed to prevent or combat infestation by organisms that can discolour or destroy the wood. These biocidal products destroy or combat harmful organisms by chemical or biological means.

Wood is one of the most ecologically friendly construction materials available, a renewable material that uses comparatively little energy in processing and is completely recyclable. Chemically treating wood to protect it should be avoided if possible, because the treatment turns wood into hazardous waste so it loses the advantage of sustainability.

Wood shrinks and swells as humidity changes. The maximum shrinkage rate for central European timber types is on average axial shrinkage 0.3 %, radial shrinkage 4 % and tangential shrinkage 8 % (Fig. 4). The large tangential value is explained by extensive radial crack formation (shrinkage cracks). If cracks of critical depths develop (Fig. 5), an expert should assess them to ensure that the structure's load-bearing capacity is maintained.

### Stone

Building with stone once involved great artisanship, as Gothic cathedrals still prove today. For a long time it was easier and more efficient to build vertically upwards than in a horizontal direction. The stone arch, whose origins go back to Roman times, became the archetype of bridge building. The Romans were able to bridge large spans using very flat arches (Fig. 9).

Natural stone is divided into igneous stone types (e.g. granite or basalt) and sedimentary stone (e.g. sandstone or limestone). Both types can be used for building bridges. Stone's compressive strength depends on its weight, which can be up to 240 N/mm<sup>2</sup> – a figure that even ultra-high strength concrete barely reaches.





9



10

Further important parameters to consider are the stone's durability, type of joining and workability. A look back at stone arch bridges, some of which have withstood assaults from the weather (and other things) for over 2,000 years, testifies to this material's durability. Stone is a very robust material and cutting and milling machines that can cut very precisely have made working it much easier and less expensive. It is now possible to exactly cut impact surfaces, the precondition for a sound transfer of forces and high load-bearing capacity. This also means that very thick layers of mortar can be dispensed with, because the transverse expansion of mortar joints can lead to damaging transverse stresses in the stone. In combination with other materials in particular, exciting designs can be created with stone (Fig. 8), which is why a renaissance in the use of this familiar and natural material would be highly desirable.

### Concrete

Many concrete and stone bridges can be categorised as »solid bridges«, but the two materials have very different applications. Concrete can basically only absorb compression stress. However, if it is reinforced, it can also bear tensile stress and can then be used as a flexural or even tension element. Owing to its formability and inexpensive manufacture, concrete has developed rapidly, particularly for bridge construction. The technique of pre-stressing has been used on most concrete bridges since the second half of the 20th century (Fig. 10). Pre-stressing has two very useful effects: a garland-shaped tendon profile adapted to the stress reduces bending stress, and the bridge's cross section is compressed, which prevents cracking. Tendons with tension ducts that were compressed after stressing were once almost exclusively

used, whereas unbonded tendons are now mainly used. They are easier to control, especially if they are externally attached, and can also be exchanged if necessary.

Concrete road and railway bridges are often longitudinally and transversely pre-stressed. For narrow pedestrian bridges, longitudinal pre-stressing is sufficient in the construction of slender beam and plate support structures. In using concrete it must be noted that it exhibits a time and load-dependent deformation behaviour, which is especially noticeable in bridges whose own weight is high. Shrinkage is a time-dependent drying process of concrete. After a few years, concrete reaches a final shrinkage rate of approx. 0.2 mm/m. Creep in contrast, depends on both load and duration. A simple reinforced concrete flexural beam is subject to deformation from its own weight as well as to additional creep deformation at three or four times the rate of its elastic deformation. If the stresses caused by its own weight are neutralised by pre-stressing, creep will be limited to purely normal force creep, i.e. a simple axial contraction of the superstructure and thus of the tendons. This results in a loss of pre-stressing stress of 5–10%, which must be taken into account in static calculations and in designing tendons to ensure that the support structure will function over its entire life cycle.

Concrete technology is now so advanced that very high compressive strengths can be achieved. Textile concrete, a fine-grained concrete with inlaid textile glass fibre reinforcement, is a material with potential for use in sustainable and robust structures. It could also be used to build filigree structures, because the reinforcement's concrete covering only has to cope with joining technique issues and not with corrosion protection.

The formwork facing structure, surface finish and colour of textured concrete surfaces should be precisely defined. Modifying the cement or adding pigments can also change the concrete's colour.

The reinforcement rods or mesh laid in concrete consist of ductile, malleable steel, the yield point of which is 500 N/mm<sup>2</sup>. This reinforcement is easy to weld and wound or rolled-on ribs ensure that it bonds with the concrete. Pre-stressed steels are unalloyed steels that are cold-drawn and thus three times as strong as ordinary reinforcing steels. The ensuing tempering process means that this steel has less creep, also referred to as "relaxation". Damage to many bridges shows how important it is to pay great attention in particular to the concrete covering of reinforcements and pre-stressed steel, because these elements need adequate reinforcement protection. DIN EN 1992-1-1 contains precise specifications on this issue.

- 4 Shrinkage rate and dry density of some wood types
- 5 Assessment criteria for crack formation in wood
- 6 Installing a glued laminated timber beam for a pedestrian and cycle path bridge, Steyrrmühl (A) 2008, Halm Kaschnig Architekten; Kurt Pock
- 7 Wooden support structure, Tomasjordnesbrücke, Tromsø (N) 2006, Sweco Norge AS
- 8 Combination of stone (mast) and steel cable. Footbridge over the Hessenring, Bad Homburg (D) 2002, schlaich bergemann und partner
- 9 Roman stone arched bridge, Pont Julien, near Bonnieux (F), 3rd century B.C..
- 10 Reinforced concrete bridge, La-Ferté-Steg, Stuttgart (D) 2001, asp Architekten; Peter und Lochner



11

### Steel

The most interesting types of steel for building and especially for pedestrian bridge construction are cable steel and cast steel.

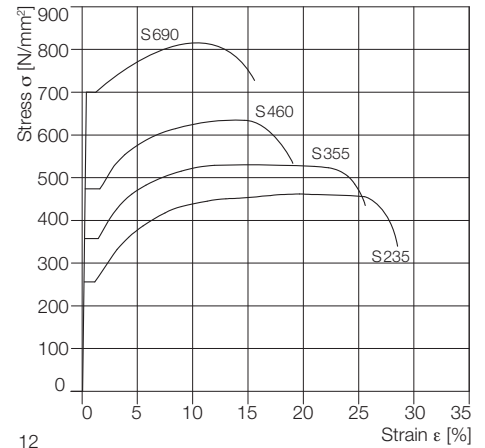
Construction steel is usually an unalloyed steel with average properties. Its yield point is 180–360 N/mm<sup>2</sup>, i.e. 1 cm<sup>2</sup> can bear a load of 1.8–3.6 t before it starts to yield, so it deforms very extensively as a result of slight load increases (Fig. 12). The yield point of fine-grained and high-strength and tempered construction steels can be increased to more than double these values. These steels are used in all areas in the form of solid, extruded or rolled profiles. A very diverse range of profiles is available, extending from open and closed through sharp-edged, round and thick profiles up to flat elements for sheet piles or plates. It is also easy to weld, which makes it possible to manufacture any type of cross section by combining individual metal elements.

Construction steel is used in pedestrian bridges in the support structure or as hollow box girders welded together for superstructures, in the form of hollow sections for piers, pylons or masts and in solid rods for tension elements (Fig. 11). Composite construction efficiently combines the advantages of concrete and steel, with steel used where tension forces predominate, while a concrete slab, which is at the same time a robust platform for pedestrian and vehicle traffic, is installed in the compression range of the cross section. Welded dowels create a shear-resistant bond. Very slender structures can be built economically in this way. Using pre-assembled steel beams as support structures for formwork or fully or partly prefabricated components saves installation time and costs. It must also be taken into account that the concrete in a composite section will try to shift under its load over time due to

creep, so the steel part of the section has to compensate for higher loads. In measuring a structure's initial state, its condition without the influence of creep and its final state once creep is complete must be taken into account.

Non-corroding steels (stainless steels) have a higher degree of purity. The material's strength, weldability and the products that can be made with it are basically similar to those of unalloyed steels. Stainless steel does not however offer the same diversity of profiles and the material and its processing are much more expensive. It is therefore used mainly for secondary structural elements such as railings or safety nets, which are exposed to high levels of mechanical stress or are hard to access.

Cold drawn wires are used to make steel cables, which increases their strength three or four-fold. It also considerably reduces their cross-sectional area, but results in a significant loss of axial rigidity, which leads to much greater deformations in the support structure. The form and geometry of its wires determine a cable's properties. Only non-moving ropes are used in bridge construction as integral parts of the structure that do not move. Two types are mainly used in footbridges: locked coil and open spiral cables. Both types of cable consist of many thin round wires (Ø up to 4 mm) or profile wires (Ø up to 8 mm), which are built up in layers and laid in opposing directions to prevent the cable untwisting when exposed to tensile loads. While open spiral cables consist solely of round wires, locked coil cables are wound with several layers of Z-wires on the outside (Fig. 13). The form closure of these wires creates a closed surface, so the wires are flat when deflected over sheaves and not pressed together at various points like the round wires, which improves their load-bearing capacity and durability.

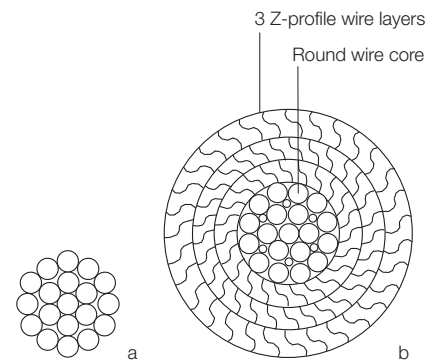


12

Locked coil cables are often used as suspension cables in suspension bridges.

They have a smooth surface, are easy to clamp and deflect over sheaves and make compact end anchorages possible (see Design and construction, p. 48ff.). Galvanised zinc-coated wires offer high-quality protection against corrosion and make further painting unnecessary. Locked coil cables are only available from a diameter of 30 mm, while open spiral cables are available from a diameter of 6 mm. Open spiral cables are suitable mainly for less stressed pedestrian bridge hanger elements, so they can be used to hang the bridge deck from a suspension cable or arch, for example (Fig. 14). Integrally moulded end anchorages make it possible to use various kinds of attachments and adjust cable lengths using threaded elements if necessary. Like normal steel, cable steel can be upgraded by adding alloying elements such as chrome, nickel, molybdenum and titanium to it to make stainless steel – an option often chosen for pedestrian bridge suspension cables, because it gives cables an even finish and they look finer. It also makes them less delicate and more resistant to corrosion and mechanical impacts.

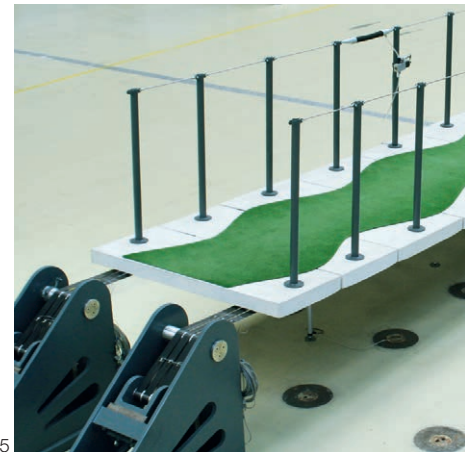
Construction steel and steel cable are moulded into its final form in rolling, pressing and drawing processes. Cast steel in contrast, combines the advantageous properties of steel with the design benefits of using cast techniques to shape the material. Cast steel's strength, toughness and workability (weldability) is now so highly technologically developed, that it is directly comparable with construction steel as a material. Making construction models, which are usually wood or Styrofoam, and casting takes special expertise to achieve a smooth, gap-free surface. Cast steel is suitable not only for pedestrian bridge cable fittings, but can also



13



14



15

be used to easily resolve geometrically complicated junctions. It also offers a way of dealing specifically with different types and degrees of stress through the application of materials (Fig. 16).

### Aluminium

A light metal, aluminium is a soft but tough construction material. Its strength is similar to steel's (up to  $700 \text{ N/mm}^2$ ) but with only a third of the stiffness ( $E = 70,000 \text{ N/mm}^2$ ). Aluminium's advantages lie in its good material efficiency, stability and low maintenance requirements. Aluminium has a breaking length three times greater than that of construction steel, an indication of its capacity despite its low weight. Its disadvantages are its high price, low fatigue strength and difficult joining technique. Manufacturing aluminium also uses a great deal of energy, which negatively affects its ecological balance. Aluminium can be worth considering for use in components exposed to high levels of mechanical stress and structural elements such as footbridge surfaces that require a minimal use of material and weight. In primary support structures too, aluminium profiles are used in standardised truss structures. Prefabricated construction methods make it very economical, but leave little leeway for individual and attractive design solutions.

### Glass

Glass can be used in pedestrian bridge surfaces and parapets. It has very high compressive strength (up to  $1,000 \text{ N/mm}^2$ ), but a comparatively low tensile strength at  $30 \text{ N/mm}^2$  with a stiffness of  $70,000 \text{ N/mm}^2$  and a specific weight of  $25 \text{ kN/m}^3$ . Because of its lower tensile strength, glass has only limited bending resistance, so its use in beam elements is restricted to small spans up to 5 m long. In longer spans,

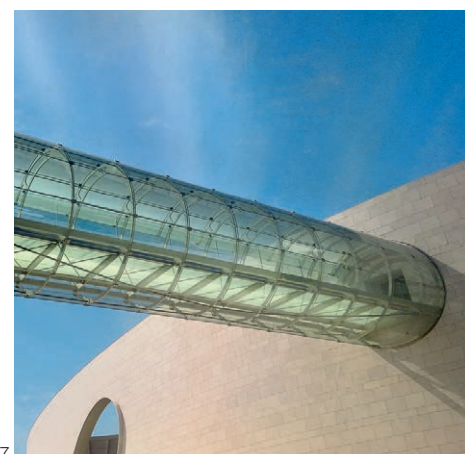
glass can be used either in a purely pressure-loaded structure (arch) or in combination with steel (Fig. 17).

### CRP/GRP

Glass is also used as a material in the form of glass-fibre reinforced plastics (GRP) or textile concrete with a glass fibre core. Fibres have a much higher tensile strength than their material itself, because a small area has statistically fewer voids than a large cross-sectional area. This scale effect means that the tensile strength of glass fibres can increase enormously, up to  $2,400 \text{ N/mm}^2$ . The material is therefore recommended for use as a composite material. Carbon-fibre reinforced plastics (CRP) are now available but still quite rarely used in pedestrian bridge construction. GRP and CRP have similar strengths, but CRP is much stiffer than GRP. Some inroads have been made towards establishing this new material in pedestrian bridge construction, but many open questions remain about its joining and dynamic behaviour. CRP in particular has great potential for use in suspension bridges and in the tension members of stress ribbon bridges. A number of universities are carrying out intensive research in this area (Fig. 15).



16



17

- 11 Steel footbridge, Hotton (B) 2002, Ney + Partners
- 12 Stress-strain diagram of various kinds of steel
- 13 Structure of steel cable  
a open; b locked-coil
- 14 Steel cable hanger elements, harbour bridge, Sassnitz (D) 2007, schlaich bergemann und partner
- 15 Stress ribbon bridge with carbon fibre stress ribbon, TU Berlin 2011
- 16 Cast steel juncture points, jetty Ökologischer Gehölzgarten, Oberhausen-Ripshorst (D) 1997, Diekmann und Lohaus; schlaich bergemann und partner
- 17 Glass bridge in a research centre, Lisbon (P) 2012, Charles Correa Associates; schlaich bergemann und partner



## Design and construction

### Design

Designing bridges is a complex task requiring experience in construction and technical expertise as well as creativity and the courage to innovate.

The design process can be divided into three main phases:

- Reviewing and clarifying the tasks involved
- Choosing a design
- Developing a design

#### Reviewing and clarifying the tasks involved

The design process involves firstly clarifying the overall conditions, ranging from topography through the type of usage up to technical parameters.

#### Topography and trajectories

The design should develop out of a thorough and sensitive appreciation of the bridge's site. A suspension bridge, a light, transparent structure, may be right for one place, while at another site an arch will be more incisive and have a greater visual presence.

A bridge's layout should be oriented towards existing route trajectories. It is important to incorporate the site's topography into the bridge's design, because this can help to keep the need for unnecessarily long ramps and for expensive and time-consuming terrain modelling to a minimum. Fluid paths without abrupt changes in direction or gradient should be aimed for, even if a straight line would be the geometrically shortest and easiest connection between two points in construction terms. Sightlines are also important, especially for pedestrian bridges in inner-city areas, where these structures can provide views over the city while at the same time contributing to giving a district a specific identity.

#### Usage and capacity

The question of the right width for a bridge must be sophisticatedly and sensitively examined and answered, because it is linked to the question of the type of usage and capacity required. A bridge designed to ensure a smooth, panic-free outflow of people from large-scale events must be designed differently to a bridge in a solitary valley that is occasionally crossed by a few hikers (see Functional requirements, p. 9f.).

Surprisingly, the most commonly applied standards do not distinguish between different loads on pedestrian bridges. They also do not specify the stiffness that such a structure must have and which deformations can be permitted. If the standardised specifications alone are followed, malleable pedestrian bridges that are susceptible to dynamic excitation will be just as permissible as very stiff, almost rigid structures (see Statics and dynamics, p. 23). This offers a great deal of scope for designers to find an appropriate and efficient solution for each individual situation.

#### Type of usage and clearance gauges

A bridge's width will depend on whether it is for pedestrians only or will also be used by cyclists and service vehicles. The clearance gauge on a bridge is 2.50 m. This determines the positioning of structural components above the deck in structures with major overhead components such as suspension bridges. Initial ideas on the possible positioning of supports, suitable span and ramp lengths, protective measures and impact risks can thus emerge from the type of usage (see Functional requirements, p. 11f.).

#### Technical boundary conditions

A site's foundation soil can decisively influence the choice of support structure.

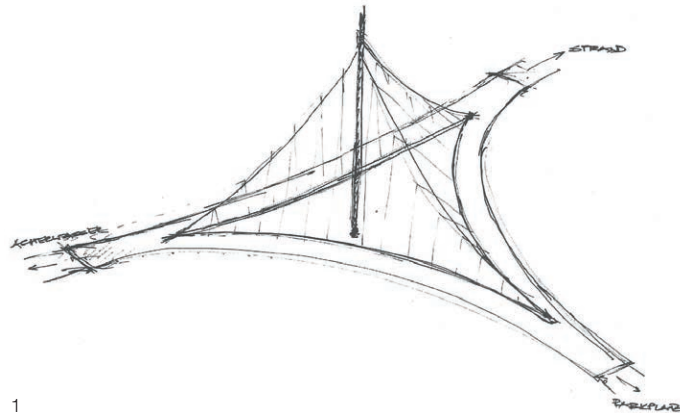
Poor soil conditions can diminish the range of possible foundations for economic reasons, making longer spans necessary. Conversely, good soil conditions on a site can favour certain constructions, if they make it easy to anchor tensile elements, making suspension structures with long spans possible, for example.

If there is initially less focus on the assembly process at the beginning of a design task, it can make a crucial difference to the design or at least to details. This question is naturally more important in the construction of major bridges than in pedestrian bridge construction, yet the mark of a good pedestrian bridge design is also the ability to erect it for a reasonable amount of cost and effort.

#### Choosing a design

Pedestrian bridges should be striking not because of their size or appearance, but due to their fineness and appropriateness. They can and should highlight innovative features in harmony with individual design tasks but should do so accessibly and on a scale appropriate to the site and its usage. The scope for design of major bridges is often defined by functionality and cost-effectiveness. Planners have much more leeway with pedestrian bridges because they are not subject to demands anything like as restrictive as those imposed on road or railway bridges. Pedestrian bridges are also often created to make a mark, confer a special identity on a site or upgrade an urban area.

Investors are usually prepared to spend more on these qualities. Pedestrian bridges are exposed to slow-moving traffic, so there is no distance between people and the structure; they can touch it directly. Users can feel, hear and see vibrations and movements much more



than they do on a major bridge, where a car or a train separates people from the bridge. Pedestrian bridge users engage in an active dialogue with the bridge structure, which they do not do with road and railway bridges. For this reason, the focus must be on the bridge's scale, structural proportions and details.

#### Developing the design

Only careful planning of the design details will produce an appealing structure. There are many examples of good design producing just an average result because planning was not consistently followed through to completion. This may be due to implementation planning being entrusted to firms that often have little sensitivity to design and have their own practical economic interests. It is then laborious and time-consuming for planners to supervise construction and to correct it if necessary. In building complex structures, it should therefore be ensured that a suitable firm is commissioned and provided with a planning procedure that comprehensively describes and specifies all of the details. This helps those responsible for executing the project to make reliable costs calculations and guarantees the client that the design

is implemented as the engineers and architects planned it, right down to the details.

Conversely, this also requires that planners incorporate aspects relevant to production and assembly, including the risk of higher costs, to reduce long disputes about the structure's feasibility. All too often, this is called into question by implementing firms seeking to assert their own influence and ideas.

The canon of pedestrian bridge forms ranges from beam bridges subject to bending loads, through trussed girder bridges, up to structures consisting entirely of compression and tension elements, such as rope and arch bridges. Their diversity is impressive and it would be unrealistic to attempt a complete description of all the types of structures and their combinations. The following notes on structural forms are therefore restricted to their main design parameters and feasibility. The examples described represent the main bridge types. The outline of various types of bridges below begins with arch bridges and goes on to describe beam and trussed girder bridges, concluding with cable-stayed and curved footbridges.

#### Definitions of terms

A bridge usually consists of a beam, also called the superstructure, and a substructure. The substructure absorbs loads from the superstructure and transfers them into the ground. The substructure includes the abutments, which mark the bridge's end points and transition into the ground, and any central supports, such as piers or pillars. Bridge bearings are points of contact between the superstructure and substructure. They ensure that the superstructure is kept as tension-free as possible and no excessive forces impact the superstructure and substructure.

Suspension bridges also include cable elements such as support cables, hangers or stayed cables, on which the superstructure is hung from pylons or masts. Arch bridges are also supported by imposts that transfer loads into the ground.

Bridge substructures, masts, pylons and imposts are set on foundations, which can either be set flat on foundation plates or deep in the ground with piles or anchors, depending on subsoil conditions.





3

## Arch bridges

### History

The arch is one of the oldest forms of support structure in bridge construction. Massive stone bridges were built more than 2,000 years ago, have lasted over the centuries, and still represent a standard today. From the 18th century onwards, the form developed swiftly with the advent of new materials such as concrete and steel.

Some imposing examples, such as the Pons Fabricius (62 B. C.) in Rome, testify not only to the robustness of these structures, but also to the great expertise of the master builders of the antiquity. In the Middle Ages, the arch bridge was in its heyday. Stone arch bridges, such as the Charles Bridge in Prague, the Stone Bridge in Regensburg and the Augustus Bridge in Dresden, were built all over Central Europe to facilitate trade. Smaller bridges too, such as the Ponte dei Salti in Lavertezzo in Switzerland, built in the 17th century (Fig. 3), show how such stone bridges continued to develop as well as the increasing use that was made of their structural potential.

Louis-Alexandre de Cessart's filigree Pont des Arts in Paris (1804) marked not only the beginning of the use of iron in

arched bridges, it is also an engineering masterpiece. The further development of iron into tough high-tensile steel made it possible to build increasingly long spans and lower gauge arches. Today pedestrian bridges with spans of more than 200 m can be built, while the longest arch bridges for road traffic have spans that are over 500 m long.

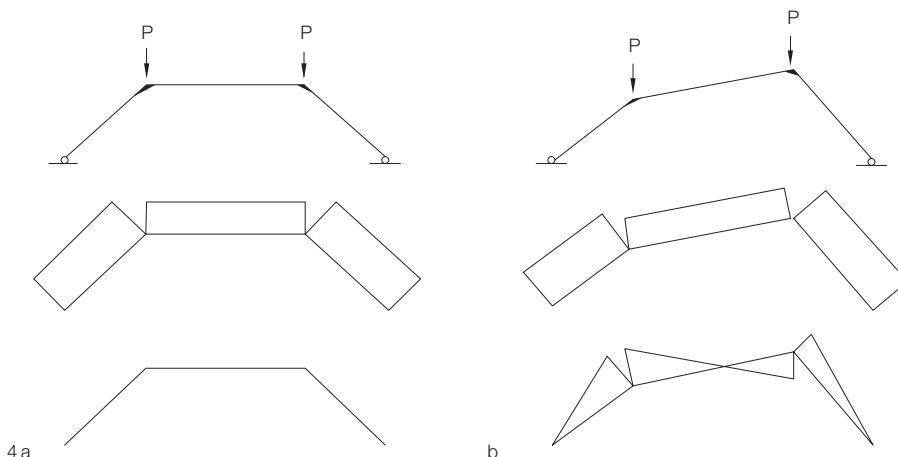
### Function

There are various forms of arches, differing in their geometry and support specifications. The geometries of arched bridges range from round and pointed arches through basket arches to segmental arches. In terms of support specifications, a distinction is made between an encastred arch and a two or three-hinged arch. Whatever the bridge's form, it is important in designing arched bridges that the geometry of the support structure follows the line of thrust, i.e. all resulting forces acting on the structure should follow the centroidal line of the arch. Put simply, this line of thrust is comparable to the line of a "standing rope" under an equal load.

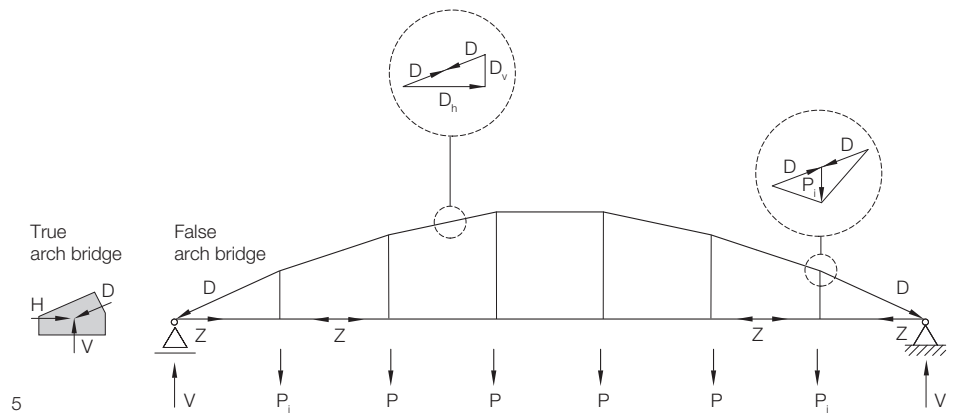
While a flexible rope must take on this distinct form, an arched support structure is different. Arches, which have to

be stiff to be stable, can also follow other arch forms. The positions of impost points and an arch's height are parameters that can be adapted to a design without breaching framework specifications. As with a rope, the ideal line of thrust of an arch is an unalterable component of an economic and efficient support structure, so it cannot be freely selected. If these prerequisites are not taken into account, normal stresses as well as bending stresses will occur in the arch, which quickly multiply the axial stress, potentially making much larger dimensions and a far greater use of materials necessary (Fig. 4).

When deflection occurs, a rope under a tensile load develops a self-stabilising force and attempts to return to its original position. Precisely the opposite occurs when a continuous beam or an arch is subject to tensile loading. The force resulting from deflection is destabilising, further deforms the arch and increases stress. At worst, this can lead to an increase in force and result in stability failure. These reactions are referred to in structural analysis as geometrically non-linear effects for small deformations. They must always be allowed for if the loads on the deformed system are very



- 1 Design sketch for a footbridge on the island of Usedom (D) 2004, schlaich bergemann and partners
- 2 Competition model for a footbridge on the island of Usedom
- 3 Arch bridge, Ponte dei Salti, Lavertezzo (CH), 17th century
- 4 Ideal (a) and not ideal (b) pressure line of an arch bridge under normal stress and bending stress  
P Load [kN]



different from those on the original system. This behaviour can be countered by increasing bending stiffness or by mounting side supports.

#### True and false arch bridges

A distinction is made in bridge construction between true and false arch bridges (Fig. 5). True arch bridges are stressed under loads by compressive force, there is no tensile stress. The roadway or walkway deck takes on the stiffening function in this type of bridge and stabilises the arch under asymmetrical loads. It can be erected or hung using rods and hangers. The rods or hangers should be very slender so that they are not subject to large bending moments. Compact cross sections with large cross section areas and low bending rigidity are suitable for the arch. The shear force of a true arch bridge's arch is transferred through the imposts into the ground below, which should be able to bear this load (Fig. 6).

The horizontal components of the arch's forces in false arch bridges, also called 'tied arch bridges' or »bowstring arch bridges«, are transferred by a tension member (Fig. 7). Tied arch bridges consist of a lower beam, which usually car-

ries the roadway or walkway deck, and an overlying slender arch from which the beam is hung with rods. The beam functions as a tension member and prevents the ends of the arch from pushing apart. False arch bridges can be built on subsoils that are less stable and able to bear loads, because no horizontal forces have to be transferred.

Another advantage of this type of arch is that it can be completely prefabricated and the arch together with the superstructure forms an inherently stable and functioning support structure. This makes it possible to efficiently assemble the entire structure by floating, lifting or sliding it into place. The superstructure stiffens the system, so it must have a corresponding bending stiffness and an appropriate structural depth.

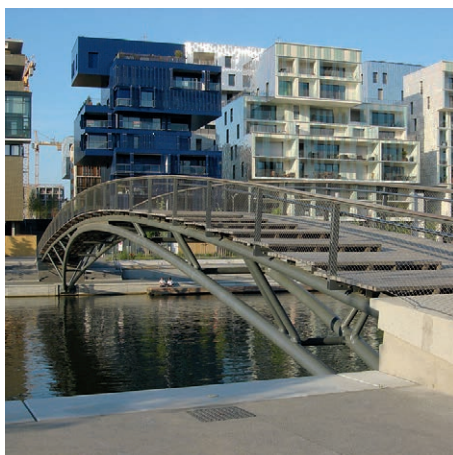
One special form of such arch bridges is the network arch bridge. Here the positioning of diagonal hangers stiffens the system through an interaction of the arch and superstructure, like the upper and lower chords of a truss system. Fatigue in the hangers can cause problems with this type of bridge. The hangers are subject to heavy loads because they transfer loads not only to the arch, but also in a longitudinal direction, functioning like

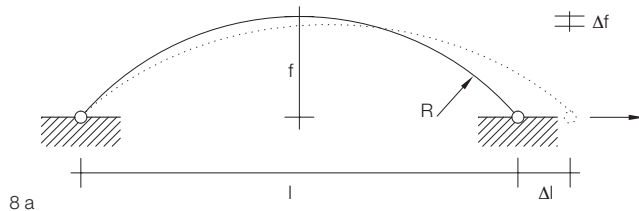
diagonals in a truss system. This means that they are exposed to large alternating loads or threshold loads.

#### Cross section

Stiffness plays a major role in the choice of a bridge's cross section, as it does with any loaded structural elements. While the hangers and superstructure prevent buckling at the arch level, the arch needs adequate transverse stabilisation. If an arch's rotation axis is above the hangers' angle of attack (analogous to a guyed mast), the hangers can provide this stabilisation by pulling the arch back into its original position if any buckling occurs. This is however rarely enough to completely stiffen the arch. If two arches are planned, they can be inclined towards each other or joined at the vertices, which improves transverse bending stiffness because the two arches stabilise each other. This is however only effective if the joints between the arches are built to be shear-resistant as frames or with crossed struts.

Such a static measure is effective, although the arches seem to merge, which "waters down" their symbolic character as classic support elements from a design point of view.





$f/l$	$R$ [m]	$\Delta f/\Delta l$
1/10	130	1.9/1
1/15	190.8	2.8/1
1/30	376.7	4.0/1
1/60	750.8	12.2/1

If this measure is not taken, the unsupported arch must have sufficient lateral strength; horizontal rectangular cross sections with low longitudinal bending strength can provide this. No particular demands are made on the superstructure of arch bridges. Open cross sections can be used for two arches that support the walkway on both sides because these do not have to provide torsional stiffness. If hangers are spaced 3 to 5 m apart, the cross section's longitudinal structural depth will usually also be sufficient for the transverse direction if the structure is 4 to 5 m wide. The superstructure of a tied arch bridge is subject to tensile forces, which must be absorbed by the superstructure cross section or by tension members added in the form of ropes. An arch positioned centrally or to one side requires a torsionally stiff superstructure, such as a steel box girder, for example.

#### Materials

Arches can be made of steel and concrete – especially high-strength concrete – or wood or stone. If wood is used, the cross section must be large, which can look clumsy. It is also only possible to provide good active wood protection, by means of a metal cover for example, to a limited extent. There are many options available for shaping a cross section using steel prefabricated arches. Apart from classic tubular profiles, welded triangular, quadratic or trapezoid profiles, which can vary in size, are regarded as reasonable and efficient cross sections that are also satisfactory in design terms.

Concrete arches are complicated to manufacture because they are built either using complex formwork in cast-in-place-concrete construction, or as jointed prefabricated components, which need an

auxiliary support structure. Because of its much greater strength, high-strength concrete allows for reductions in the cross section's surface area and in the weight of parts. If a prefabricated construction method is used, the arch's individual segments must be pressed together with pre-stressing tendons so that even if the arch is unilaterally loaded no excessive tensile stresses occur and joints stay closed. Modern arch structures made of natural stone blocks can also be built in this way. Given today's manufacturing options and in combination with other materials, such as high strength steel (cable) or glass, entirely new and exciting stone structures are now conceivable (Fig. 8, p. 28).

#### Load bearing

An arch bridge's rise should be approximately one tenth of its span length. This balances the strength ratio in the arch and the system will not be overly sensitive to soil subsidence. If lower rises are chosen, greater arch forces result. The support system also becomes increasingly sensitive to horizontal deformations of the imposts, i.e. the rise changes due to horizontal settling of the arch abutments, which can reduce the arch's resistance to buckling. Figure 8 shows how this sensitivity increases due to lower rises.

Depending on a site's soil subsidence, a planner must decide whether an arch bridge's deformations need to be specially monitored. Any settling can be compensated for by subsequently mounting backing plates so that the bridge retains its geometry.

The arch shear force to be absorbed can be calculated using an arch's rise, height and the loads to be assumed. If these are not diverted via tension members, they must be transferred into the

ground. Apart from shallow foundations, which are braced against the ground by angled base plates, deep foundations can also be used. The decision on the most suitable foundation will depend on the site's soil conditions and should be made in conjunction with a geotechnical engineer in each individual case. This also applies to all other forms of support structure and structures.

- 5 Support system of a true and a false arch bridge  
P Load [kN]  
Z Tension [kN]  
D Pressure [kN]  
V Reaction force [kN]
- 6 True arch bridge. Force is transferred from the arch directly into the imposts. Passerelle Lyon Confluence, Lyon (F) 2004, RFR Ingenieure
- 7 False arch bridge. The carriageway functions as a tension member and forces are transferred. Three Countries Bridge, Weil am Rhein (D) 2007, Dietmar Feichtinger Architects; Wolfgang Strobl
- 8 Arch deformation  $\Delta f$  in dependence on rise  $f/l$  at constant horizontal displacement  $\Delta l$  using an example of an arch with a 100 m span
- 9 Underspanned arch bridge with pre-stressed tie rod to stabilise the arch. Pedestrian bridge over the Allmandring, Stuttgart (D) 1994, Kaag + Schwarz; Gustl Lachenmann





10

## Beam and slab bridges

### History

A beam or slab bridge is the simplest and oldest form of pedestrian bridge. The first beam bridge spans were determined by the length of the available materials, such as tree trunks or stone slabs (Fig. 10), which limited the spans of such structures. Bridges with larger spans could only be built after the introduction of primary supports in truss, suspension or arch bridges to take on the support function. The beam or slab became a secondary support element.

The development of steel cross sections and new steel-reinforced and pre-stressed concretes meant that from the 18th century more efficient beam bridges could be built. These new materials made it possible to economically build bridges with longer spans. Famous 19th century engineers such as Robert Maillart, Eugène Freyssinet, François Hennebique and later Ulrich Finsterwalder and Fritz Leonhardt played decisive roles in developing this kind of bridge.

### Function

Beam bridge supports can consist of a single-span or multi-span girder, a continuous girder or a cantilever girder. Flexibly mounted single-span girders represent the simplest form of beam bridge (Fig. 13). They are statically determinate, simple to design, and allow for quality prefabrication and assembly. The beam's own weight, and the traffic load it is subject to, impose compressive stress on the top side and tensile stress on the underside (Fig. 12).

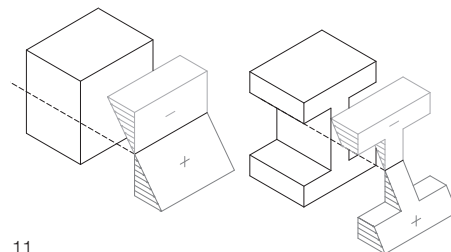
The bending moment of a single-span girder under uniformly distributed loads has a parabolic curve. A support beam with a cross section of uniform height is therefore not optimal because this form does not adequately account for the distribution of forces within the beam.

Based on these considerations, a series of support forms intended to also save materials were developed. If the cross section design follows this parabolic curve, special forms such as parabolic or lenticular trusses can be built, which reduce material use and weight. This optimisation is especially important in longer spans to prevent the structure's own weight from overburdening the support system so that it can bear only light traffic loads.

Even if it is a fish-belly truss, a beam with a rectangular cross section must still bear a good deal of unnecessary ballast. As the triangular stress diagram shows, only the cross section's edges are fully utilised (Fig. 11). They are furthest away from the centroidal axis and therefore have the greatest share of the cross section's resistance to bending. All other parts of the cross section are far less loaded due to their position near the centroid, yet they still load the beam with the same weight as the highly stressed peripheral fibres do.

A consolidation of material in the middle of the span makes such single-span girders seem unwieldy and less transparent. This can become even more extreme if they are standardised and assembled in a series to form a chain of single spans for reasons of economy and technical assembly.

Another way of reducing the cross section of a beam bridge is to fix the beam to the abutments. It can be anchored there so that it cannot warp, which results in a statically indeterminate system with altered stress distribution. The maximum loads are now on the abutments. These loads are reduced by a third in the middle of the span compared with those on a single-span girder. This distributed stress means that the cross section's structural depth can be lower, even at the same



11

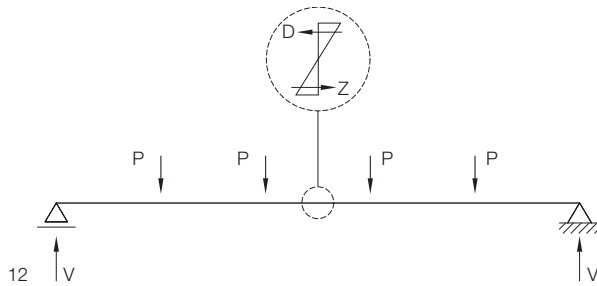
span length, and the clamped beam is only approximately 66% fully loaded at a constant structural depth compared with a single-span girder (Figs. 14 and 15, p. 40). These fixed end moments must however be anchored in the abutments and transferred into the ground, which can make larger and more complex foundations necessary.

A continuous girder behaves similarly to a clamped beam and its balanced moment means that it can be far more slender and homogeneous than a series of single-span girders.

Further advantages of continuous systems are that there is less deformation and no high-maintenance joints are necessary. Multi-span girders are however more complicated to build because they can rarely be manufactured in one piece and construction joints can make design and corrosion protection problematic.

A clamped beam's static indeterminacy gives rise to yet another, more important difference from statically determined systems. The stress of the clamped beam depends on the distribution of stiffness, while the stress on a single-span girder does not depend on stiffness. Conversely, this means that through an appropriate distribution of stiffness, i.e. the cross section's structural depth, stress on the clamped beam can be controlled (Fig. 17, p. 40).

If a cross section depth for a beam is chosen that follows the stress of the clamped beam, the stiffer cross section will impose a greater load on the abutments and the change in stiffness will transfer additional stress to them. In extreme cases, i.e. with a theoretical cross section depth of zero in the middle of the span – in fact a central joint – the result will be two cantilever arms. This system is also advantageous because of



the further reduction in the load of its own weight precisely in areas in which a minimised cross section would normally work against these loads. They require only very low cross section depths at the ends of the two cantilevers – in the middle of the clamped girder's span – meaning that such single-span girders can be made very slender and transparent.

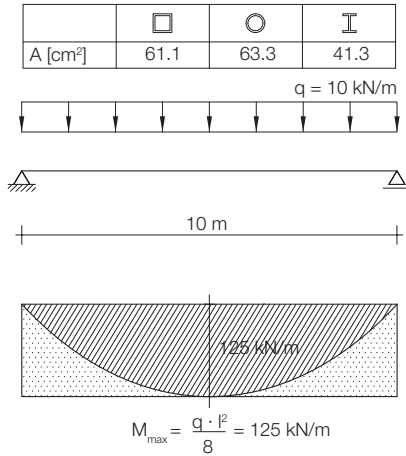
#### Cross sections

The cross sections available for beam bridges range from pre-stressed and steel reinforced concrete to pure steel and wood cross sections up to different

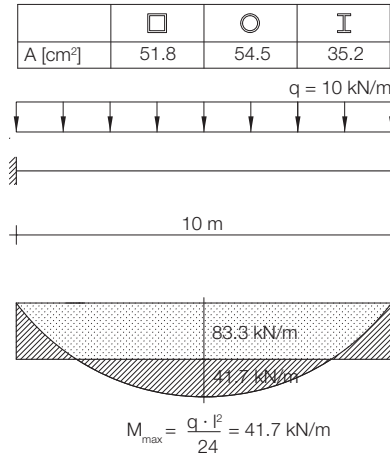
composite cross sections made of concrete and steel or wood and concrete. Tensile stresses are considerably reduced in pre-stressed concrete cross sections due to parabolic pre-stressing tendons, so slenderness ratios of  $l/35$  to  $l/40$  can be achieved. In steel construction, box sections made of sheet metal welded together have been shown to be especially efficient. They are very stiff at low weights and make it possible to build spans of up to 100 m, although they also have the disadvantage that they require a structural depth of 2.20 to 2.80 m (approx.  $l/45$ ),

- 10 Stone slab bridge, Clapper Bridge, Dartmoor (GB), 13th century
- 11 Stress distribution under the moment load of a rectangular solid cross section compared with a double T-cross section (tensile: +, compressive: -)
- 12 Beam bridge support system
- 13 Beam bridge with box girder, Bridge memorial, Rijeka (HR) 2004, 3LHD arhitekti; C.E.S. Civil Engineering Solutions





14



15

which detracts from the bridge's transparent, light appearance. Compared with relieved support structures, such beam bridges involve a high use of materials and their large cross sections also make them harder to assemble. Trough cross sections have the advantage that they do not require any additional railings, although their effective structural depth is similar to that of box sections.

Apart from loading, a bridge's deformations must also be taken into account. They indicate the system's sensitivity to dynamic excitation, and in the case of concrete bridges, their sensitivity to creep. Creep deformations make up approximately three to four times the dead-weight deformation. They can be accounted for in advance by exaggerat-

ing the height, i.e. increasing the extent to which a beam is made higher in manufacturing to include the expected sag in the middle. However, theoretical calculations of such will vary to a certain extent because the material's precise behaviour is difficult to predict. Such long-term deformations should be especially taken into account in concrete beam bridges with long spans to prevent an impression of sagging in the completed bridge.

**Load bearing**

Fixed points on supports or abutments transfer the horizontal loads of bridges. The fixed point remains in a resting position during longitudinal expansion, while all the other points shift along an imaginary line between the fixed point and the point under consideration. This

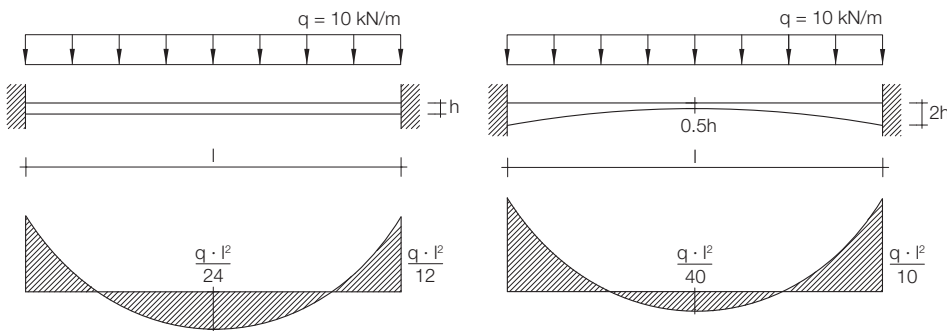
must be especially accounted for in aligning the bearings of curved layouts. These fixed points are usually attached in places where horizontal forces can be efficiently transferred, commonly at bearings, where large vertical forces also occur.

Displacement paths must be able to be absorbed as tension-free as far as possible, apart from slight friction, by bearings, joints and transitions. Bearings are either prefabricated standard parts or individually manufactured assembly parts. Their size and construction depends on loading and the length of displacement paths (see Finishings, p. 72). Elastomeric bearings in the form of fixed bearing pads or deformation slip bearings are normally used for slab and beam bridges. Roller, pin or spherical bearings are rarely used for larger loads.



16

- 14 Single-span girder: stress distribution and resulting required cross section
- 15 Clamped beam: stress distribution and resulting required cross section
- 16 Integral beam bridge, pedestrian bridge over the Carpinteira river, Covilhã (P) 2009, João Luís Carrilho da Graça; AFA Ingenieure
- 17 Stress distribution of a clamped beam by comparison:
  - a constant structural depth
  - b uneven structural depth
- 18 Stress M with prescribed displacement path  $\Delta s$  for different support conditions
  - Geometrically linear: firmly clamped supports
  - Geometrically non-linear for small deformations: elastic restraint
  - Geometrically non-linear for large deformations: flexibly mounted supports
- $\alpha$  twisting angle of supports
- M Bending moment due to displacement [kN/m]
- E Bending stiffness [N/m<sup>2</sup>]
- I Moment of inertia [m<sup>4</sup>]
- l Support length [m]
- 19 Stress on a cross section with the same area but varying form



17 a

b

Rocking piers can also react to a longitudinal expansion of the superstructure by tilting. Through a butt strap joint they can be made to absorb tensile and compressive forces, which standardised bearings can only do to a limited extent. If the deformations are larger and rocker member lengths short, it must be taken into account that horizontal forces will result from the tilting and that these can impose additional horizontal loads on the superstructure and on the rocker member's anchoring.

**Integral and semi-integral bridges**

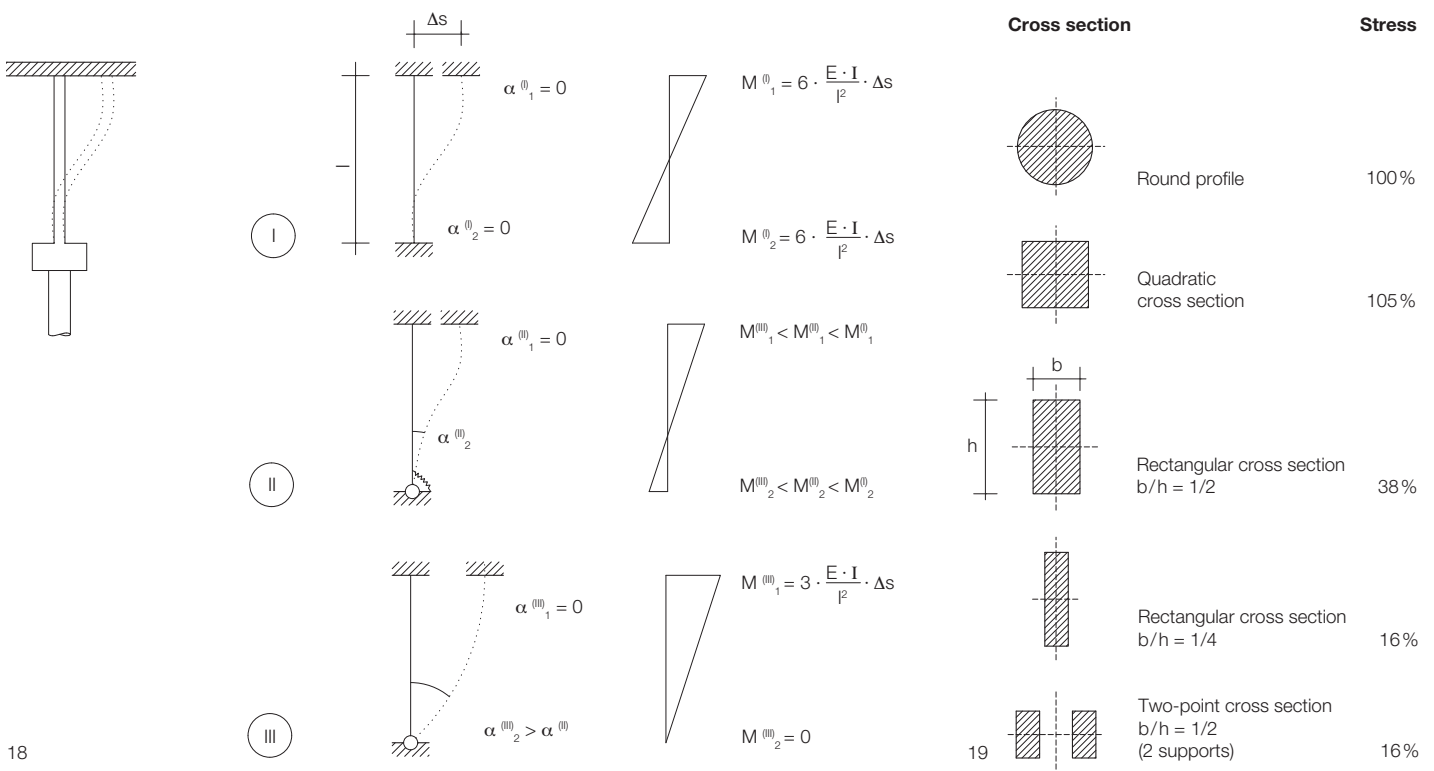
Bearings and joints wear out and must be regularly inspected, maintained and replaced, so it is better to dispense with bearings if possible, which can also reduce maintenance costs and make structures more robust. Bridges without

bearings are also called integral bridges and a distinction is made between semi-integral and integral bridges. Integral bridges dispense with bearings altogether, while the superstructure of a semi-integral bridge is connected with the substructure partly with and partly without bearings.

An integral bridge has no definitive fixed point (Fig. 16) so the bridge can expand and deform wherever it encounters the least resistance. The so-called elastic fixed point is also the system's resting point, from which the bridge deforms. This fixed point must not necessarily coincide with a support point. Piers and abutments in structures with integral bearing are subject to widely varying horizontal loads. Anchoring the piers in the superstructure and in the

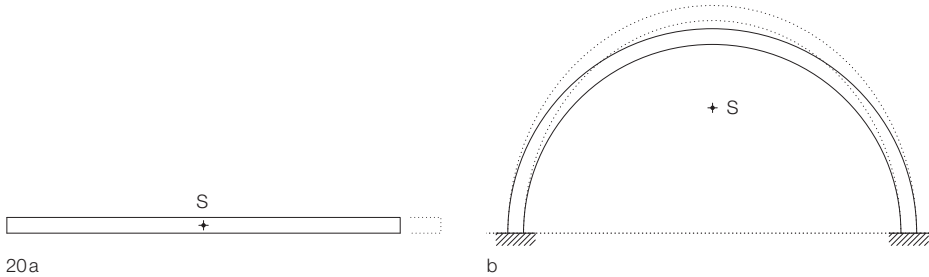
foundations shortens the piers' buckling length, but it is subjected to an additional bending stress from the superstructure displacements.

Because superstructure displacements are almost independent of the stiffness of the piers, the question is how this constraining force can be dealt with by selecting a suitable cross section. The pier cross section must be balanced; on the one hand, it must provide sufficient buckling stability to absorb forces, on the other hand, it must be flexible enough to not unnecessarily draw forces from the imposed longitudinal displacements of the superstructure. The piers' length has a major influence in this context. The longer the deformable part, the lower the stress. This dependence is quadratic, i.e. with a double deformation length the stress is reduced to a quarter, so the



18

19



pier should be as long as possible. As Figure 18 (p. 41) shows, a flexible joint at the foot of the support halves the stress on the fixing point to the superstructure, reducing it to half. With a so-called elastic end restraint, i.e. not a complete end restraint, but also not a flexible connection, a state between a geometrically linear and geometrically non-linear state for large deformations occurs. For this the foundation must be as slender as possible. If it is a deep foundation, it should be built with just one row of piles if possible, to reduce torsional rigidity.

Cross sections that are slender in a longitudinal direction and stiff in a transverse direction are suitable as supports. Fig. 19 (p. 41) shows the different stress levels for structures with the same area of cross section, same head displacement, but different forms of support. Their shorter deformation lengths make splayed Y-shaped supports unsuitable for absorbing constraining forces. V-shaped supports are very stiff and allow only slight deformations without causing large constraining forces. Various approaches are used for the abutments of an integral bridge.

The bearing situation on the abutments should either be as flexible as possible or completely rigid. An elastic bearing can be built with one or two flexible, slender wall plates, depending on whether clamping is required or not. For the stiffness of the wall plates, a similar principle applies as for the piers: the more flexible they are, the lower the stress. If reinforced concrete is used, it is advisable to include possible increases in deformation and the associated loss of stiffness as a result of crack formation (geometrically non-linear state for small deformations) in planning considerations.

Backfilling the abutment should have as little as possible or no influence on the restraint behaviour. This is ensured by decoupling or padding the abutment with a soft layer of soil or stabilising the ground behind the abutment so that there is complete separation and no interaction takes place.

With rigid supports, the bridge is completely held by the abutments and compensates for any variations in length with internal strain.

If there is a change in temperature,  $\Delta T$  the tension-free expansion is calculated as follows:

$$\Delta s = l \cdot \alpha_t \cdot \Delta T \text{ [m]} \quad (I)$$

The extent of the change in length does not depend on the cross section's surface area; it is determined solely by the thermal expansion coefficient and differences in temperature. A temperature increase of 30°C would for example cause a 100 m long bridge to elongate to the following extents:

- Steel bridge by approx. 36 mm ( $\alpha_t = 1.2 \cdot 10^{-6}$ )
- Concrete bridge by 30 mm ( $\alpha_t = 1.0 \cdot 10^{-6}$ )
- Wood or glass bridge by 24 mm ( $\alpha_t = 0.8 \cdot 10^{-6}$ )

The axial force required to compensate for this deformation is:

$$F = \Delta s \cdot E \cdot A / l \text{ [N]} \quad (II)$$

If you apply in (II)  $\Delta s$  of (I), the forces result in

$$F = \alpha_t \cdot \Delta T \cdot E \cdot A \text{ [N]}$$

and the stress in

$$\sigma = F/A = \alpha_t \cdot \Delta T \cdot E$$

- $\Delta s$  Change in length [m]
- $l$  Original length [m]
- $\alpha_t$  Coefficient of linear expansion [1/K]
- $\Delta T$  Change in temperature [K]
- $F$  Axial force [N]
- $A$  Cross section area [m<sup>2</sup>]
- $E$  Modulus of elasticity [N/m<sup>2</sup>]
- $\sigma$  Stress [N/m<sup>2</sup>]

Two things are interesting here: the force does not depend on the bridge length and the stress is, like changes in length, independent of the area of the cross section. It can therefore be advisable, especially with long bridges, to choose integral solutions. Large tensile forces must be anchored in the abutments of such structures, but the piers can be very simply built without constraining forces, because every point of the bridge remains in the resting position.

In contrast to straight bridges, a curved bridge can divest itself of constraining forces through changes in the curve of the horizontal section, resulting in much lower stresses (Fig. 20).

Trends indicate that integral bridges will significantly influence bridge construction in future. The technical processing of such bridges' support structures must be approached in a far more precise and sophisticated way. Individual elements' stiffness can influence the whole support structure's stress condition. This means that the dimensions of the structural elements are mutually dependent, so it is no longer necessary to pursue the classic segregation and separate treatment of foundations, substructure and superstructure.



21

## Truss bridges

### History

Although Leonardo da Vinci and Andrea Palladio were designing truss systems in the 15th and 16th centuries (Fig. 21), the term 'truss bridge' was first coined in the 18th century. The first classic truss bridges were also built of wood in that century. Lattice truss bridges, with criss-crossed wooden slats connecting the upper and lower chords, were first built in America in the early 19th century. In the years following, cast iron profiles improved this system.

One example of this type of structure is the Rhine Bridge in Waldshut, which opened in 1859. The further development of steel as a material and new calculation methods devised by engineers and mathematicians such as Karl Culmann, August Ritter and Luigi Cremona culminated in the building of a series of truss bridges in the second half of the 19th century (Fig. 22). A Schwedler truss imposes purely tensile loads on its struts. Friedrich August von Pauli and Isambard Kingdom Brunel developed and built fish-belly truss girders with spans of up to 130 m.

New railway bridge construction systems were developed in North America during the country's industrialisation. James Warren connected the bridges' upper and lower chords with criss-crossed diagonals, developing the pure form of the truss. In a Fink truss the beam's truss rods overlap, so they provide very efficient and transparent bridge supports.

### Function

A truss is a structure that consists of several rods that are connected at both ends. Each rod forms part of at least one triangular panel. When loads are imposed on structures built on this principle, the truss girder's individual rods are subject only to axial forces (Fig. 23, p. 44). While only the edges are fully exploited under bending stress, the entire cross section is loaded under axial stress. Truss structures are therefore very efficient. They dispense with unnecessary material and are therefore also light.

Forces in a truss – as long as they are statically determinate – can be identified by graphic methods such as the Cremona diagram without complex calculation. This purely axial stress means that each rod can be optimally dimensioned and used.

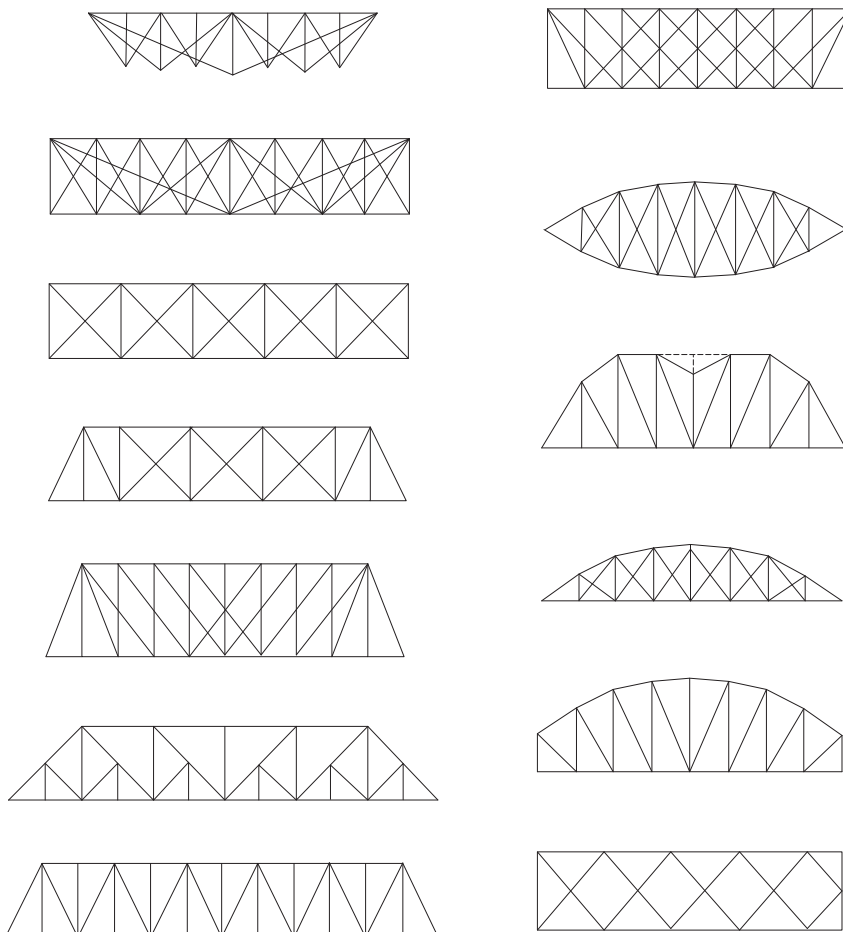
If the cross sections of the individual rods are adapted to compressive and tensile forces and this results in a discernible difference, such support structures can be optimised and »thinned out«.

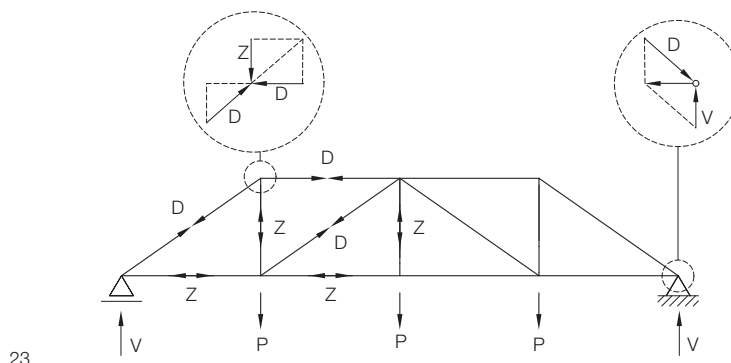
20 Displacement due to elongation  
a straight design  
b curved design

21 Covered wooden bridge, Ponte degli Alpini, Bassano del Grappa (I) 1569, built after a design by Andrea Palladio

22 Various truss forms (left column from top, followed by right column from top): Fink truss, Bollman truss, Howe truss, Pratt truss, Whipple truss, Petit truss, Warren truss, lattice truss, Pauli-fish-belly truss, Schwedler truss, parabolic truss, semi-parabolic girder truss, Engesser truss

22





23

### Underspanned systems

Trusses can be positioned above or below the bridge deck. In planning underspanned structures it must be ensured that any clearance limits and flood protection regulations applying to the area under the bridge are observed.

A single-span beam with an underspanned truss has the advantage that the lower chord is only subject to tension, which makes slender structures possible. Function and structure can also be combined to make the walkway function as a compression chord, which efficiently uses structural elements. Simple underspanned systems have few connection details and are uncomplicated to assemble. Their spans can be up to 40 m long. The superstructure of a bridge with a longer span will require more support to limit its own structural height (king posts). This can be provided in the form of a fish-belly trussed girder with a curved tension chord, such as the one in the Traversiner Steg I, a pedestrian bridge that was destroyed by a rock fall in 1999 (Figs. 26 and 27). Omitting the crossed rods will result in a self-anchored suspension structure with the superstructure as a tension chord, such as the multi-span, slightly curved Living Bridge in Limerick (Fig. 28 and 29). Its underspanned truss level has also been tilted outwards, making the underlying truss visible to users and giving the system more transverse stability. Akio Kasuga's Seishun Bridge in Tsumagoi in Japan was built in segments and has an underspanned hanger cable at the height of the superstructure. This served in the installation of the concrete railing segments and in the bridge's final state provides additional reinforcement for the support system.

### Through truss systems

If the truss is above the walkway, it is a through truss system. The upper chord's

stability plays an important role here. Upper chords above single-span beams are subject to compression and there is a risk of lateral deflection. This must be prevented either by a proportionate transverse stiffness of the truss girder, or the struts and diagonals must prevent lateral deflection by exercising an appropriate framing action. If trusses are positioned along both sides of a walkway and both chords are above the bridge's clearance gauge, connecting and filling the upper chords can result in very efficient reciprocal stabilisation. It also changes the bridge's character: users no longer walk along but through the support structure. The upper chord of a cantilevered truss is subject to tension, which makes it possible to build smaller cross sections. There is however a risk of lateral deflection of the upper chord, which can be countered by clamping the struts in the superstructure.

### Forms of support structures

Truss girders with parallel chords are very differently stressed, as the graduation in the cross section suggests. This type of truss is especially suitable for systems made up of equal, standardised individual parts, because all the elements have the same length and the detail points are repeated. If the upper chord follows the stress distribution, as it does in a trapezoidal or parabolic girder, the forces are more balanced.

A lenticular or fish-belly truss has two curved chords, which means that a straight walkway or roadway deck must often be either hung or erected. Choosing a geometry that follows the stress distribution will result at best in making continuously uniform chord cross sections possible.

Diagonals can also be very differently stressed depending on their position and direction. Here too, it is advisable

to differentiate between cross sections subject to compressive and tensile stress. Struts under compressive pressure must always be rigid so that they do not buckle. In contrast, struts under tensile stress can be flexible compact solid rods or cables.

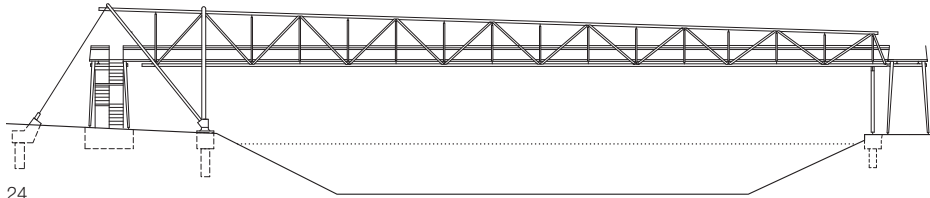
Apart from classic truss structures, other, further developed truss forms have been used in some pedestrian bridges. One of these is the inverse Fink truss, which is based on the classic principle of the Fink truss. The German-American engineer Albert Fink developed this type of support structure for railway bridges. Nesting underspanned systems provides an extremely transparent support system for single-span beams, although the many overlaps make a restless impression. This principle looks more harmonious in an inverse through truss system because there is only one overlap, so the system looks more 'readable' and clearer (Figs. 31 and 32, p. 46).

One special kind of truss structure is a trussed triangular mesh tube. It gives users walking through it an exciting three-dimensional interior space. The circular cross section means that the tubes tend to take on an oval shape under lateral loading. To counteract this, individual elements must either be inherently stiff enough or the cross section's rings (ribs) must be sufficiently strongly shaped. The curved surface makes connecting the truss rod nodes more complex and expensive compared with those in straight trusses.

### Materials

#### Wood

Truss structures were initially built using wood because wooden rods and joints were relatively easy to make. Some of the first simple wooden truss bridges are still



24

standing today, such as the Chapel Bridge in Lucerne in Switzerland, which is still in use more than 600 years after it was built.

Wooden structures quickly reach their limits with larger spans because carpentry joints cannot transfer large forces. In particular, the inability of joints to transfer tensile forces without slipping limits the span lengths of such wooden bridges. Only with the advent of new materials, such as iron and steel, were methods of jointing developed that could transfer larger forces, making longer spans possible.

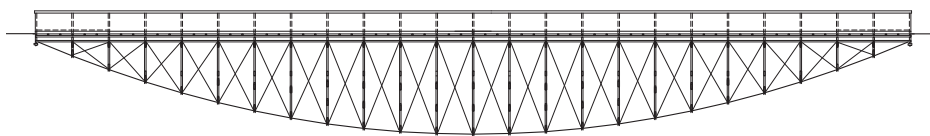
The old wooden structures owe their robustness and durability to a thorough protection of the wood, which then, as now, could be best provided by shielding that bridges' structural elements are adequately ventilated.

A roof for example, not only fulfils this function, but can also serve as an element for stabilising the truss's upper chord. Damp spots, such as those under metal coverings, can destroy wood and should be avoided.



25

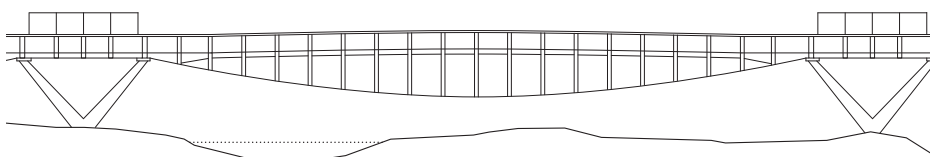
- 23 Support system of a truss bridge
- 24 View, bridge over the Rhine-Main-Danube Canal, Regensburg (D) 1998, Felix Schürmann Architects; Mayr und Ludescher Ingenieure; Scale 1:500
- 25 Through truss system, bridge over the Rhine-Main-Danube Canal
- 26 Longitudinal section, Traversina Steg I, Viamala (CH) 1996 (destroyed in 1999), Branger, Conzett & Partner; without scale
- 27 Underspanned system with diagonal reinforcement Traversina Steg I
- 28 View, Living Bridge, Limerick (GB) 2007, Wilkinson Eyre Architects; Arup; without scale
- 29 Underspanned system without diagonal reinforcement, Living Bridge



26



27



28



29



30

### Steel

This material's greater efficiency means that steel trusses can be used not only for much larger spans, but steel coated with corrosion protection can also be unrestrictedly exposed to weather without its integrity being impacted, which allows for open structures without protective roofing. The truss elements can consist of standard rolled sections or composite, welded cross sections. High-strength cables, steel sheeting or tie rods are often used as tension elements. These elements' connection points – the truss joints – can be made of metal and welded together or cast in steel. Joints that follow the flow of forces and look very compact and well proportioned can be cast in this way. This is an important aspect in designing pedestrian bridges whose details need to be to scale and proportions balanced.

Ideally, these joints should be flexible to exclude the possibility of secondary bending stress, also called secondary truss stress. Flexible joints are however much more complex to manufacture, so it would seem reasonable to tolerate the secondary stresses occurring in rigid joints, which can make up 10–20% of the total stress load.

### Concrete

The advantage of using concrete as a material is that it is easy to shape and can react very well to all static and topographical constraints. One interesting example of a concrete truss bridge is the Alfenz Bridge in Lorüns in Austria (see p. 94f.). This bridge's concise design, presence and its sculptural reinforced concrete structure make it a striking feature in the landscape. Concrete makes the deliberate irregularity of the diagonals, the positioning of which is based on bionic principles, seem natural and fluid.

The development of high-strength concrete, which can reach compressive strengths of up to 200 N/mm<sup>2</sup>, opened up new potentials for concrete truss bridges. Using prefabricated parts that are pre-stressed in a pre-stressing bed and very light and thus easy to transport makes it possible to build filigree truss structures.

### Load bearing

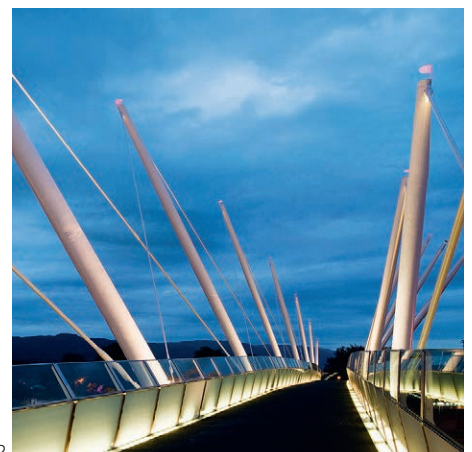
Their longer spans mean that truss bridge bearings have to absorb greater forces than simple beam or slab bridges do. If the capacity of elastomeric bearings is not sufficient, roller or spherical

bearings can be used. Truss girders should be mounted tension-free, because the eccentric position of the point of support with respect to the support structure's axis means that apart from axial stress, additional moment stress can also occur.

Shallow foundations and all kinds of deep foundations with piles, anchors or in extreme cases a diaphragm wall or well foundations can be used, depending on stresses and the site's soil conditions.



31



32



33

## Suspension bridges

### History

Suspension bridges originated in the advanced civilisations of Asia and South America. In India and Peru there are still suspension bridges with plant fibre support ropes (Fig. 33).

In Europe in contrast, suspension bridges were completely unknown for a long time and their history only began with the development of tough steel. Their tension members were initially forged chains. Only in the 19th and 20th centuries were wire ropes developed, mainly in France, Switzerland and America, so that continuous tension elements could be manufactured. Wire cable was also easier to build with, which made it possible to create greater spans. The Pont Charles-Albert, built near Cruseilles in France in 1839, was one of Europe's earliest wire cable suspension bridges. The Brooklyn Bridge in New York (1883) represented the final breakthrough of wire cable and launched the race for increasingly long spans. Suspension bridges with spans of over 3,000 m are now regarded as constructible.

### Function

Suspension bridges offer a range of construction options, from classic back-anchored or self-anchored suspension bridges through bridges with angled rope planes or lateral guying, to multi-span suspension bridges.

In back-anchored suspension bridges, the tensile force of the support cable is completely anchored into the ground, whereas with self-anchored suspension bridges only the vertical component is transferred into the ground, while the horizontal component is diverted via the superstructure with the opposite side (Fig. 34, p. 48).

In a back-anchored system, the support cable is first mounted, then the super-

structure can be hung in sections, which is a great advantage over self-anchored suspension bridges. With this type of bridge, it is important that the two opposite anchorage points of the support cable are connected. This means that the superstructure must be at least partly complete before the support cable can be loaded. Alternatively, the support cable can be temporarily anchored in the ground to transfer the horizontal forces into the ground, which involves some expense and effort.

Although it could be thought that under-spanned bridges without crossed struts should be classified as truss or even beam bridges, they belong strictly speaking to the category of self-anchored suspension bridges, although in modified form. Underspanning (hanger ropes) bears the superstructure on supports (hangers), which in turn diverts the horizontal forces in the system and also ensures stiffness under loads not corresponding to the structure's geometry. Underspanning can be provided in the form of cable, metal or concrete, while the use of concrete is only advisable in construction terms if it is pre-stressed and can absorb tensile forces without developing large cracks.

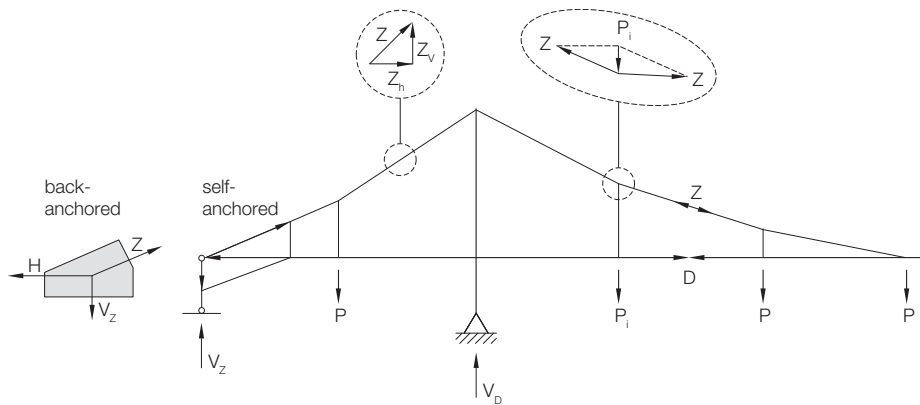
Suspension bridges are very efficient support structures, because they require only a minimal use of materials. Their tension line is directly developed out of the moment distribution. The disadvantage of suspension bridges is however, that loads such as individual loads or unilateral traffic loads that do not correspond with the bridge's own weight can lead to extensive deformations. The greater the force in the support cable, the lower the levels of deformation it demonstrates.

The level of forces in the support cables is determined by the rope's geometry and its own weight. As well as a bal-

anced ratio between span length and sag (camber), the ratio of the structure's own weight to traffic load therefore plays a major role in suspension bridges. Balanced force ratios in the support cables, guys and masts are achieved with a rise of approximately 1/10 to 1/12. The greater the bridge's own weight, the less sensitive it is to deformations caused by traffic loads. This is a major difference between these structures and cable-stayed, beam and truss bridges. In the latter bridge types only the stiffness of structural elements contributes to deformation, not the forces in the structural elements.

If the hangers' angles are changed, the system's stiffness will also be modified. Angled hangers slightly improve stiffness, while zigzag diagonal hangers completely change a bridge's support characteristics so that they resemble those of a truss bridge. The compressive forces occurring in a truss in a suspension structure can however only be completely absorbed by the cables if there is enough own weight. The weight pre-stresses the hanger ropes, i.e. the reduction in tensile forces enables them to absorb compressive forces from traffic loads. To prevent the hangers from developing fatigue problems, it must be ensured that they are adequately pre-stressed with sufficient weight so that they can absorb the compressive forces from traffic loads.

- 30 Triangular and square mesh truss tube, Peace Bridge, Calgary (CDN) 2012, Santiago Calatrava
- 31 Inverse Fink truss, Royal Victoria Dock Bridge, London (GB) 1998, Lifschutz Davidson; Technician
- 32 Inverse Fink truss with various outward tilted struts, Forthside Bridge, Stirling (GB) 2009, Wilkinson Eyre Architects; Gifford
- 33 Simple suspension bridge made of osiers in the Ladakh region (IND)



34

While suspension bridges can only be built as major bridges with very long spans due to their complex manufacture and susceptibility to dynamic excitation, pedestrian bridges with medium-length spans of 30 to 100 m make much less static and dynamic demands on their support systems. This makes it possible to build very light and aesthetically appealing bridges in this smaller-scale range (Fig. 35).

**Support elements**

*Support cables*

The main support element of a suspension bridge is the support cable. Support cables have to be able to absorb large axial forces using as little material as possible. To avoid greater bending stress resulting from changes in curvature and redirection, continuous support cables should be as flexible as possible. While it can be interesting and economical in building shorter spans to use support cables made of articulated chain consisting of chain links or steel sections, continuous cables, which ideally meet all support requirements in one tension member, are mainly used for longer spans. On the one hand, high-strength tempered steel is three or four times as

strong as normal construction steel and therefore has a very favourable ratio of own weight to strength (see Materials, p. 27). On the other hand, the cross section, which is made up of many individual wires, only has a fraction of the stiffness that a solid steel rod of the same diameter would have. This also makes redirection without large additional bending stress possible.

Locked coil spiral cables in particular have proven their worth in pedestrian bridge construction. At its core, this type of cable consists of several round wires laid in opposing directions. Z-wires form the outer layers, providing a closed structure. The outer Z-wires create a form closure so the cable can absorb transverse compression through the arching effect. This means that the cables can be bent and clamped without damaging the wires and weakening them.

Locked coil cables are far less resistant to fatigue than parallel wire bundle cables, which is especially important in the stayed cables of transport bridges. Their much lighter traffic means that pedestrian bridges are subject to smaller alternate loads, so the fatigue resistance of structural elements tends to play a less crucial role in them.

Cables must be pre-stretched to forestall any remaining deformation, also called creep deformation. To do this, the cable is ratcheted up to five times its service load. Despite pre-stretching, cables will continue to creep. The remaining 3 to 4 mm of a 10 m-long cable must be taken into account in determining length by shortening it accordingly in advance. This means that suspension bridges usually sit a little too high shortly after completion and only gradually creep into their final position over the course of the next year or two.

The wires in the end anchorages are cast in a conical sleeve with a zinc-aluminium-magnesium-copper alloy called Zamak. The cylindrical ends can transfer their forces either directly to an anchorage body (Fig. 39) or via cast-on eye plates to a bolt connection (Fig. 38). While a cylindrical spelter socket allows for length adjustments through bearing plates, this option is not available with an open spelter socket.

Cables are protected against corrosion by a Galfan coating. Galfan is a metallic coating for round and profiled wires consisting of an alloy of approximately 95 %



35



36



37

zinc and 5% aluminium and is made with a coating weight per unit area of around 300 g/m<sup>2</sup>.

Since no further coating is necessary, the cable can retain its structured metallic surface. Galvan coatings are designed to be durable for up to 50 years. If the anti-corrosion protection deteriorates or is damaged, the coating can easily be renewed with the application of a new layer.

As classic suspension bridge support cables run over masts to the abutments, some geometrical considerations must be kept in mind within this context. Put simply, the support cable force is anchored by a brace, which consists of the mast and the retaining or continuous support cable (Fig. 46, p. 52). The forces in this system depend on the tilt of the mast. If the mast stands in the angle bisector, then the support cable forces will be equal and no tangential forces have to be transferred to the mast. If however, the mast moves out of this ideal position, differential forces occur in the support cables and the forces affecting the mast change. If the mast tilts towards the bridge's centre, the force in the mast increases; if it tilts in the opposite direc-

tion it decreases. Differential forces from the support cables must be transferred into the mast. If a cable saddle is used, forces must be transferred via friction between the rope and rope groove and, if necessary, via additional clamping in the saddle.

With respect to cable saddles, some construction parameters must be complied with. A minimum radius of 20 times the cable diameter is required for cable redirection. The saddle's length and size will be a consequence of the cable diameter and the aperture angle between the cable and the mast. So-called 'end trumpets' must be installed at the end of the saddle. These help to minimise local bending stress in the cable if the angle of the support cable changes. Due to its often-complex three-dimensional geometry, it may be advisable to manufacture the saddle using cast steel. This also provides a harmonious transition into the mast shaft.

One alternative to cable saddles are strap anchors. In contrast to a cable saddle, they transfer the rope's entire force into the mast head. The rope force is diverted into the mast head with the opposite side and transfers its vertical component (with a tilted mast the component in the axial

direction of the mast) to the mast shaft. These anchorings, which are usually made of metal welded together, require very careful planning due to the large forces and complex geometry involved, as well as the often-cramped space available if a proper transfer of forces, perfect assembly and good weldability is to be ensured.

#### Hanger ropes

Open spiral cables are suitable for use as hanger ropes, because they are much less loaded than the support cables. They usually consist of 7, 19, 37, 61 or 91 round wires and are made with diameters ranging from 10 mm up to 36 mm. Open spiral cables are not as stiff as locked coil cables, especially if they are made of stainless steel. Due to the lower stress, the end fittings can be pressed onto the open spiral cables.

The required press or anchoring length is approximately seven times the rope's diameter and makes the fittings look elongated. A distinction is made between fork, eye and threaded fittings (Fig. 42). If adjustment is necessary, an additional turnbuckle can be added, although it must be ensured that the turnbuckles are appropriately secured.



38



39

- 34 Support system of a suspension bridge
- 35 Self-anchored suspension bridge, Glacis Bridge, Minden (D) 1994, schlaich bergemann and partners
- 36 Cable clamp hanger rope with redirection
- 37 Cable clamp with bolt connection and end fitting
- 38 Open spelter socket
- 39 Cylindrical spelter socket



40



41

Hanger ropes are connected to the support cable by rope clamps (Figs. 36 and 37, p. 49). These consist of two half shells clamped to the support cable with high-strength pre-stressed bolts to form a slip-resistant joint. The amount of pre-stressing depends on the tangential or slip forces to be transferred. In the case of vertical hangers these increase with the support cable's angle, i.e. clamps near the mast, which are usually connected to the most heavily loaded hangers, have the greatest slip force. In dealing with widely varying slip forces it is advisable to graduate the hanger clamp cross sections. Because these clamps are often cast parts, it must be determined whether it is worth going through the complex and costly process of manufacturing new foundry models or whether the same clamps can be used throughout.

Before choosing suitable hanger anchoring, it must be determined whether the hanger rope length will have to be corrected. It must be taken into account that diagonal hangers are much more sensitive than vertical hangers to changes in the length of support structure components. The choice of hanger anchoring will also depend on whether any imprecision

in the bridge construction has already been identified when hangers were fitted and will have to be taken into consideration and whether expected long-term deformations (e.g. creep effect of rope or the concrete superstructure) can be predicted and calculated precisely enough. An engineer must decide in each individual case whether a non-adjustable, fixed anchoring will suffice or whether a turnbuckle will be necessary.

Hanger ropes can be connected to the superstructure by a simple butt and strap joint (Fig. 40) or by bollards. The latter will only function however with double-shear hanger loops, which are also run over a support cable clamp. While a threaded fitting can be adjusted, all the other connections mentioned here are rigid and do not allow for any length adjustment. A special kind of anchoring is the looping of hanger ropes through the substructure's lower edge, which is only possible with symmetrical anchorings or those positioned opposite each other. This obviates the need for the two fittings and anchoring on the superstructure, however cable saddles are required which are no less complicated; the cable

is clamped to these to prevent it slipping through should a unilateral load be imposed upon it.

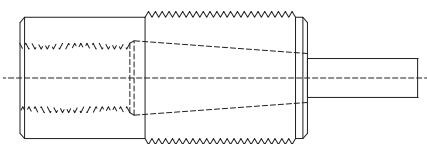
**Support cable anchorings**

Cables must be anchored in the abutments and anchor points or to the superstructure so that tensile forces can be transferred into the ground or the superstructure's cross section. This can be done either with brackets, which are clamped with tendons to concrete bases, or by building or welding steel elements onto the abutments or superstructure.

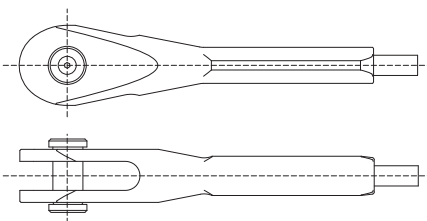
In the cross sections of concrete superstructures with minimised heights there is often not much space available, so forces can only be transferred over greater lengths. This is achieved using serrated steel strips, which ensure a continuous transfer of force.

Loop anchoring means that two rope end anchorings can be dispensed with, although cable saddles with suitable openings in the abutments to thread the ropes through will be necessary (Fig. 43).

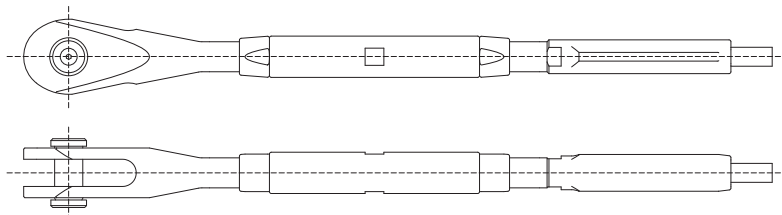
In choosing support cable anchorings it must be taken into account that if a cable is clamped in a butt and strap joint and



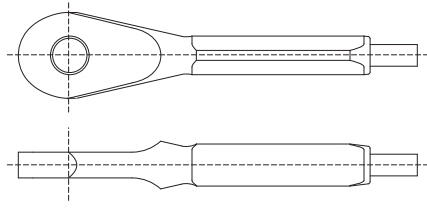
a



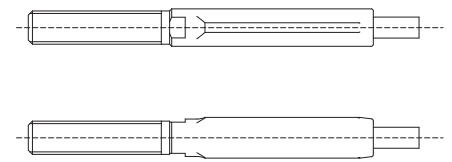
42 b



c



d



e



43

looped it cannot be adjusted. Should adjustment be necessary, a cylindrical anchor head with washers or braced anchoring must be used.

#### Masts, pylons

A mast is subject mainly to compressive forces from the support cables, so buckling stability issues will determine its dimensions. The bending and deformation components from the mast's own weight must be taken into account with tilted masts. In connection with great compressive forces, these can substantially increase stress (geometrically non-linear for small deformations). With skilful pre-cambering, the bending moment from the structure's own weight can be balanced by the pre-camber and compressive force moments. Pressure-stable or buckle-resistant cross sections must be as stiff as possible, meaning that from a static-constructive and economic point of view, hollow sections are most suitable for these as they have the largest possible amount of material at the greatest possible distance from the centre of gravity and therefore have a large radius of gyration.

$$i = \sqrt{I/A}$$

(moment of inertia  $I$ , cross section area  $A$ )

If open sections are chosen, much more material will have to be used to achieve an identical radius of gyration, i.e. the same buckling stability.

Relieved cross sections also follow this principle of maximum »material removal«. They are more costly and complex to manufacture, but compared with hollow sections can look more structured, yet sometimes also 'busy'.

Stress on the mast follows a cigar-shaped parabola. By dividing the mast into three conical sections at the top, the foot and a middle section with a consistent cross

section, this course can be traced with a reasonable amount of effort. The mast looks more slender and its function as a pendulum rod is made clear.

Self-supporting masts can be stabilised either by anchoring or by using support cables. If only two cables stabilise the mast, it must be ensured that recovery forces always compensate and the cables do not exert any down forces on the mast if it is deflected, so that the mast is pulled back into its initial position. This is ensured if the mast's centre of rotation is lower than an imaginary line between the two cable anchorings (Fig. 44, p. 52).

This problem will not occur with three cables or if two masts mutually stabilise each other with connecting bars. In this case, horizontal forces can be directly transferred using guy ropes or by a framework effect.

A mast can also be installed with a flexible joint in the form of a sphere at the end of its lower conic section (Fig. 45, p. 52). This ball bearing allows for large changes of angle, which is advantageous, especially if the mast has to be tipped from a vertical position into its final tilted position during installation.

Alternatively, bearings such as spherical bearings or rubber pot bearings can be used. These are however only suitable to a limited extent for flexible joints and often require a diameter similar to that of the mast itself, which prevents the mast being tapered down to its foot and can make it look clumsy.

Anchored foundations and abutments to which the mast's main support cables are anchored must be designed to take tensile and horizontal forces. Immovable heavyweight foundations are suitable for this purpose, although the large volumes they require tend to make them uneconomic.

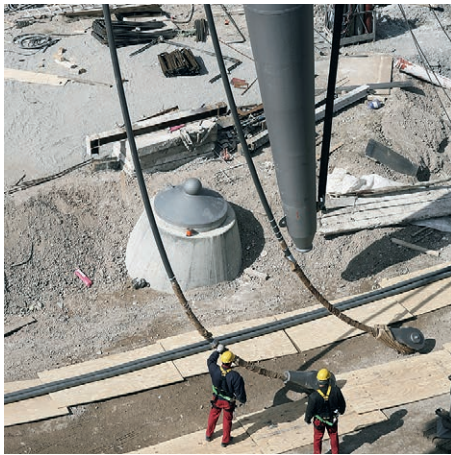
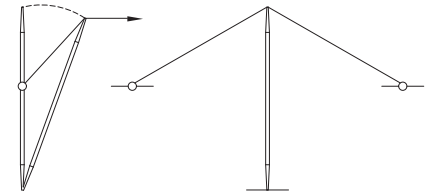
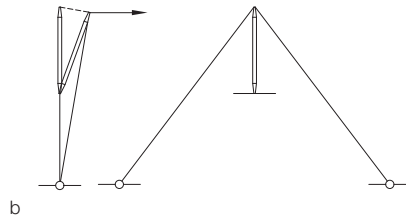
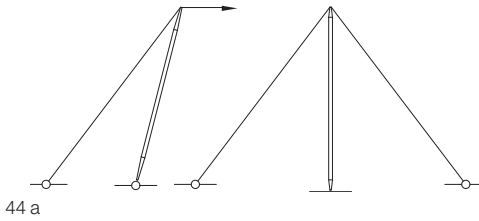
Anchors or piles are often a better solution because they anchor forces in the ground and the adjacent ground can be activated. If the tension rods have a robust corrosion protection and if tests show that they are stable after installation, they can be used as a permanent anchor without restriction.

#### Superstructure

A superstructure's dimensions will depend on stress and often on admissible local deformations. Installation considerations, such as an assessment of dynamic properties, must also be taken into account here. If the bridge is hung on both sides, the superstructure does not have to be torsion-resistant and demands on the cross section's bending stiffness are also low, because the cable support structure provides the necessary stiffness. A simple slab, which could be either a purely concrete cross section or a composite cross section made up of a steel beam with a thin concrete slab laid on it, will suffice. The latter has the advantage that the steel beam can be pre-installed with the cable support structure and the concrete elements can be added in a second step as finished or semi-finished parts.

The cross section of a self-anchored suspension bridge is subject to compressive forces, so its superstructure requires axial

- 40 Anchorage of cables to the superstructure with a fork fitting
- 41 Support cable anchorings on a superstructure with support cables anchored to cross girders
- 42 Cable end connections
  - a Cylindrical spelter socket with an external and internal thread
  - b Fork fitting
  - c Fork turnbuckle
  - d Eye fitting
  - e Threaded fitting
- 43 Bearer cable redirected over a cast saddle in abutments



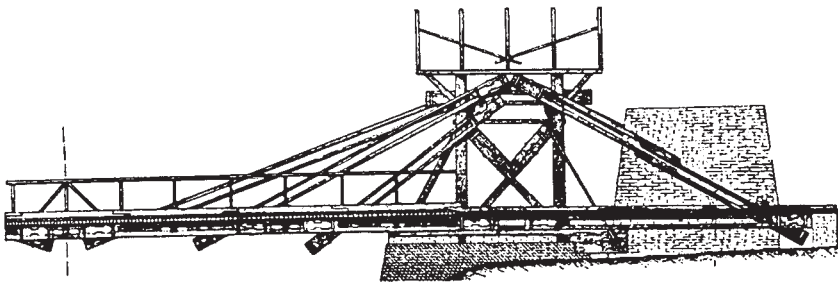
stiffness. Purely concrete cross sections, which are subject to compressive forces through the diversion of rope forces, are suitable here. This compressive force has a positive effect, because the tensile stress from bending is reduced so the cross section will not break up as quickly. The great disadvantage of a self-anchored suspension bridge is – as already mentioned – its complex installation. The superstructure is first completely manufactured using falsework and only then can it be hung in the cable support structure. Segmental manufacture followed by an assembly of the superstructure in mid-air is only possible if the support cables are temporarily back-anchored, which is often depicted in spectacular photos of the construction of large suspension bridges.



A suspension bridge's superstructure must be able to absorb horizontal forces and excessive relative displacement between the cable support structure and the superstructure, which can lead to skewing of the hangers, which must not be allowed to occur. If a fixed point is chosen on one of the abutments, very large longitudinal displacements will occur in the other abutment and in back-anchored structures. This can lead to the relative displacement between the cable support structure and superstructure described above. Floating support of the superstructure is therefore often advisable, especially for larger spans. With floating support there is no designated fixed point, the bridge deforms freely and the horizontal longitudinal forces must be compensated for by activating recovery forces in the cable support structure. One advantage of this kind of support is that the resting point, also called the elastic fixed point, is near the bridge's middle.

From there the bridge moves in both directions and the deformation paths of the superstructure are halved. If floating support is used, it must be ensured that the superstructure does not make excessive pendulum movements. To limit these, retainers can be installed to prevent any exceptionally large longitudinal deformations, such as those caused by very large numbers of pedestrians or even earthquakes.

Suspension bridges can deform very severely, especially under unilateral traffic loads and the support cable can shift horizontally in the direction of the stress. This can be prevented by immovably joining the superstructure in the middle of the bridge horizontally to the support cable so that it functions as a support bar for the support cable. This prevents horizontal displacement of the support cable and reduces vertical deformations. If the support cable is anchored in the superstructure, it must be taken into account that differential forces are transferred from the support cable into the superstructure, so it is necessary to clamp the continuous cable. This also only works if the superstructure has a fixed point for absorbing horizontal forces and is not resting on floating support.



47

### Cable-stayed bridges

#### History

As early as the 18th century, bridge designers were thinking about using angled stay rods or cables to rig overhanging structures. Carl Immanuel Löscher made the first known design of a guyed wooden bridge in 1784 (Fig. 47). In the early 19th century, Claude-Louis Navier developed cable-stayed systems, distinguishing between a radial (fan) and parallel (harp) arrangement of stays. Only very few 'true' cable-stayed bridges were however built. Most such structures are combined suspension/cable-stayed structures, such as the Albert Bridge over the Thames in London (1872) or the Brooklyn Bridge in New York (1883). The first true cable-stayed bridges were however only built in the mid-20th century because they react far more sensitively to various construction tolerances than suspended structures do. Minor errors in length are immediately noticeable and produce widely varying, barely controllable forces in the angled cable stays, resulting in excessive stress on the superstructure. Improved manufacturing options have now solved these problems, so cable-stayed bridges can now be very effi-

ciently and economically manufactured in cantilever construction without scaffolding. This has led in recent decades to a rapid increase in span lengths, which can now reach up to 1,100 m for large bridges.

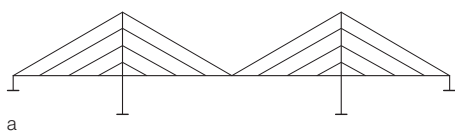
#### Function

A cable-stayed bridge superstructure hangs directly from a pylon or mast on angled and tensioned ropes or cables. They therefore belong, strictly speaking, to the category of truss bridges, because they are made up of individual triangles with a systematic separation of tensile (stay cables) and compressive (superstructure, pylon) elements. This truss effect also makes them much stiffer than suspension bridges. Stay cables can be arranged in the form of a harp or a fan. A fan arrangement is more favourable for economic and construction reasons (Fig. 48). In an ideal fan arrangement all the stay cables meet at one point, concentrating the anchorings at the mast head. A clean constructional implementation is not possible due to the size of the anchorings, unless these are positioned next to each other, which results in large mast heads.

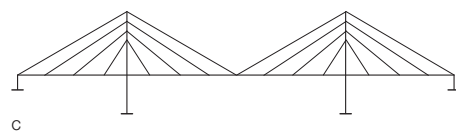
- 44 Stabilising of a mast with various stresses
  - a Guyed mast
  - b Free-standing mast. The mast tips if the mast foundation is above the cable anchoring. If the mast foundation is under the cable anchoring it remains stable.
- 45 Setting of a mast on a spherical joint
- 46 Mast with cable saddle and spherical joint, Glacis Bridge, Minden (D) 1994, schlaich bergermann und partner
- 47 Guyed wooden bridge by Carl Immanuel Löscher, 1784
- 48 Longitudinal arrangement of stay cables
  - a Harp arrangement
  - b Fan arrangement
  - c Semi-harp arrangement
  - d Asymmetrical arrangement

In a parallel arrangement of angled stay cables – harp formation – the mast shaft is subjected to much higher stresses, because the cables act on it at varying heights, which is why the so-called semi-harp form has become established. In this form, the anchorings of the angled cables are pushed together opposite the 'harp' in the direction of the mast head and can be easily anchored while exerting only slight bending stress on the mast.

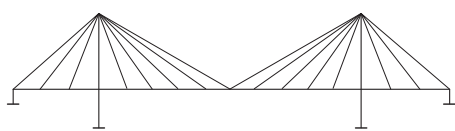
As pedestrian bridges have to bear much lesser loads than major bridges, special forms of mast geometry and cable anchorings are technically feasible for them. Masts can be asymmetrically positioned, tilted or straddled, or even form an arch or be bent. Interesting geometrical forms can be produced by varying the heights of cable anchorings, although such extravagant arrangements result in greater forces and use of materials. In a structure with a curved mast and harp arrangement, the force from the angled cable stays must be in equilibrium with the redirection force, which results out of the curve of the mast subject to axial stress, otherwise the mast will be subject to significant bending moments that it will only be able to absorb through a reinforced cross section.



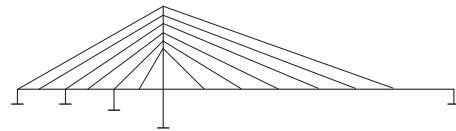
a



c



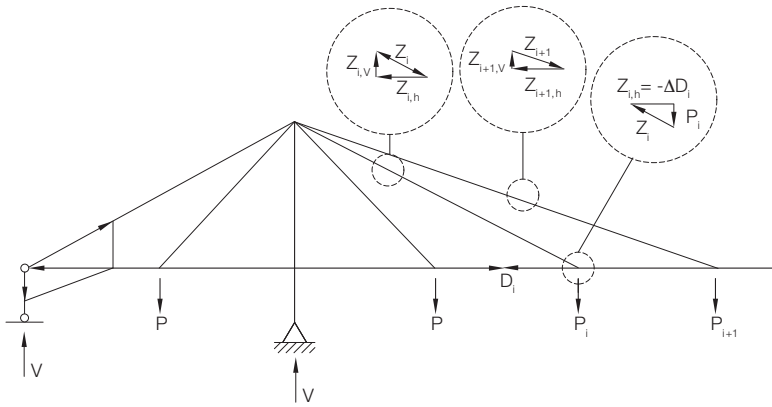
48b



d

While the massive dimensions of classic cable-stayed major bridge structures make them look imposing but well proportioned, they can often make both a linear and static impression in a much smaller pedestrian bridge.

One of the reasons for this is the strict geometry of these structures. More fluid, organic forms are more appealing. Classic cable-stayed bridges tend to be more frequently represented in the major bridge category and less so among smaller, less austere pedestrian bridges.



49

Leaving behind this familiar arrangement of mast, superstructure and cables and two-dimensionality and venturing into other spatial dimensions can result in very interesting and appealing cable stayed structures (see Curved bridges p. 60ff.).

**Support elements**

*Stay cables*

Cables should be at an angle of no less than 20 degrees. Open spiral cables can be used as angled cable stays for smaller diameters; locked coil cables are more suitable for larger diameters. Stranded

cables made up of many seven-wire strands bundled together and usually used in major bridge construction, can be used but have the disadvantage that the anchorings are complex and costly, because every strand has to be individually anchored with wedges. This results in very large anchorings, which can look out of scale in smaller pedestrian bridges. Very long cables sag, which can cause them to lose stiffness. In spans of less than 100 m with a correspondingly high level of stress in the cable this tends to play a less crucial role with thinner pedestrian bridge cables.

Cables can usually be adjusted to compensate for tolerances, with the cable adjusted to the right force. This is important because significantly changed stresses can occur due to errors in length not only in the cables but also in the superstructure. Apart from being hung from both sides, bridges can also be hung on one side or in the middle. The superstructure of a straight bridge with just one rope plane must have sufficient torsional stiffness. Curved bridges with just one rope plane can use the curve to transform the torsion in bending. Here more expensive and complex box beam sections can be dispensed with and open cross sections, which must have higher bending stiffness, can be used.



50

*Superstructure*

Because of the angled cable stays, the superstructure has to absorb compressive forces, meaning that adequate axial stiffness must be taken into account in planning. From a construction and economic point of view, massive concrete slabs or composite sections are more suitable than pure steel sections, because the angled stay cables provide them with beneficial external pre-stressing.

Cable-stayed bridges can be built using a cantilever construction method without scaffolding, beginning with the mast and working down both sides, which is a great advantage compared with suspension bridges. They are assembled either out of completely prefabricated components, which are lifted into place, or with semi-finished parts, which are finished by being cast in concrete in-situ. To create a composite section, the main steel girder is first installed, then concrete is poured onto the composite slab or the structure is completed with prefabricated



51

#### Load bearing

As with suspension bridges, heavyweight foundations or tie rods or piles absorb the vertical tensile forces at the ends of the bridge. External longitudinal forces are transferred either to fixed points on the abutments or via a bearing to a pylon or mast. Floating support, which provides no definitive fixed point, is not very economical because horizontal longitudinal forces are transferred to the mast head by the angled cable stays and then through the bending of the mast down into the foundations and thus have to travel long distances. The mast must also have sufficient bending stiffness.

- 49 Cable-stayed bridge support system
- 50 Cable-stayed bridge with pylons on each side of the deck, bridge over the Hoofdvaart Canal Hoofddorp (NL) 2004, Santiago Calatrava
- 51 Mast head with cable stay anchoring, Passerelle des deux Rives, Strasbourg (F) 2004, Marc Mimram
- 52 Cable stay anchoring to a substructure, Bridge over the Hoofdvaart Canal



52

parts. This construction method saves time and money.

Massive wooden cross sections are also suitable as superstructures, because the joints of individual superstructure elements are subject to compressive stress. They can be joined with contact splices, which are much easier to make in wooden structures than tensile splices. Active protection of the wood is usually provided by a metal cover.

Glass can also be suitable for such superstructures because of its high compressive strength, although glass walkways can cause problems because they are slippery when wet. For this reason, glass bridges are usually only built indoors. If glass panels have to be replaced, it can be carried out either using a temporary support or by diverting the compressive forces to temporary compressive elements.

Cables should be spaced in the superstructure to ensure that no excessive forces occur in the angled cable stays and that cable cross sections are not disproportionately large. Distances of 3 to 5 m are not only economical, they can make the rope plane look flatter, which produces interesting three-dimensional geometries, especially in curved and unilateral arrangements. These spacings allow for a slender superstructure beam with an overall depth ranging from 30 to 50 cm. If the distances between the cables are longer, the superstructure must have greater longitudinal stiffness so that it can transfer loads to the angled cable stays. The transfer of loads in a transverse direction is only decisive for the superstructure's overall structural depth if the bridge is wider than 5 to 6 m.

Cables can be anchored to the superstructure and mast either with a butt and strap joint or fastened over cleats or

tubes (Fig. 52). Redirection over the masthead is also possible, however, as it is very complicated to run many cables over special cable saddles, this kind of anchoring is very rarely used in pedestrian bridges. If a cable cannot be adjusted, by a turnbuckle for example, other means of adjustment must be provided in the superstructure anchorings by lining them with washers or by using adjustable bolted connections.

#### Masts and pylons

The stress on a mast depends on its support and the arrangement of cable anchorings. With a flexible joint at the foot of the mast and a concentrated anchoring of cables on the mast in a fan formation, almost exclusively axial forces occur in the mast (Fig. 51). If the foot of the mast is fixed, the mast's buckling length is reduced, although bending moments result from this fixing, in particular under asymmetrical traffic loads, which can defeat this advantage. If it is fixed, it is also not possible to taper the mast to its foot, which can make it look clumsier. If the cable anchoring at the mast head is widely spaced, as in a harp formation, the mast will be subject to additional bending stress, because the cable forces are distributed. The same applies to the cross sections of pylons and the masts of cable-stayed bridge as for those of suspension bridges.

Cable-stayed bridge mast forms range from freestanding masts through to H or A-shaped pylons. In H-shaped masts, the rope plane can be arranged vertically, while lateral loads are transferred by the supporting framework effect. In contrast, in the case of an A form and an angled rope plane, loads are transferred far more efficiently by a type of brace, in this case the mast shafts.



53 54

**Stress ribbon bridges**

**History**

Stress ribbon bridges made of natural fibres have a long tradition throughout Asia and North America. The oldest existing multi-span stress ribbon bridge is the Anlan Bridge in south-western China. It is said to have been built in 960 A. D. and has a total length, incredible for those times, of about 300 m, in eight spans, each up to 60 m long. It hangs from ten thick bamboo ropes that run through wooden guides on both sides (Fig. 53). The Incas in South America further developed stress ribbon bridge construction. A bridge made of plaited osier ropes once spanned the 45 m-wide Apurímac Gorge in Peru. Suspension bridges tended to be preferred in later eras, because stress ribbon bridges, with their steep slopes at each end, made going hard for pedestrians. Only with the development of tough, high-strength steels in the 19th century did stress ribbon bridges again start to be built more frequently. Today's modern stress ribbon bridges are made up of one or more tensile members consisting of pre-stressed tendons or stress ribbons. Their characteristic sag in the middle makes these types of structure especially

suitable for pedestrian bridges, because the bridge's bobbing and swaying will not necessarily be regarded as disturbing (Fig. 56).

**Function**

The load-bearing behaviour of stress ribbon bridges is very similar to that of back-anchored suspension bridges. The difference is that the tension member is directly used as a walkway. The force *F* in the stress ribbon depends on the span length *l*, the distributed load *q* and the sag *f*. The maximum slope at the ends of the bridge can be determined by means of the sag *f* and span length *l*. As Figure 55 shows, there is a linear dependency between the rise and the slope and also between the rise and the force in the stress ribbon – although they are in inverse proportion. This means that doubling the slope also doubles the rise but halves the force and the following equation results:

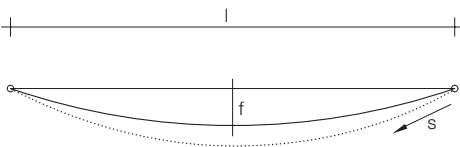
$$s = \frac{4 \cdot f}{l} \text{ [%]}$$

$$F = \frac{q \cdot l^2}{8 \cdot f} \text{ [kN]}$$

- s Slope [%]
- f Sag [m]
- l Span [m]
- F Force in the stress ribbon [kN]
- q Load [kN/m<sup>2</sup>]

Slopes of up to 6% are usually acceptable for pedestrian bridges. This results in a *f/l* ratio of 0.06/4 = 1/67. If this is compared with the *f/l* ratio of approximately 1/10 recommended for suspension bridges, it becomes clear that this type of bridge must transfer much greater forces, which must be anchored at some cost and effort. Spans of up to 130 m are possible with these rise ratios, but they require very large stress ribbon cross sections and huge foundations. This is clearly evident in the Millennium Bridge in London for example, which is not a stress-ribbon bridge, but a suspension bridge with a comparable rise ratio. Its superstructure hangs on four steel cables, each 120 mm in diameter. The average span length is 130 m with a rise of approximately 2.30 m.

Stress ribbons can extend over one or several spans. Like multi-span suspension and cable-stayed bridges, multi-span systems have their own specific



Forces in the stress ribbon [kN]  
q = 10 kN/m<sup>2</sup> for a width of 1 m

s [%]	l [m]			
	20	40	60	100
4 %	2500	5000	7500	12500
6 %	1667	3333	5000	8333
8 %	1250	2500	3750	6250
10 %	1000	2000	3000	5000
12 %	833	1667	2500	4167

55 56



- 53 Anlan Bridge, Dujiangyan (CN), 960 A.D.
- 54 Support system of a stress ribbon bridge
- 55 Forces in the stress ribbon depending on span length and slope  $s$
- 56 Steel stress ribbon bridge, Aaresteg, Auenstein (CH) 2010, Conzett Bronzini Gartmann
- 57 Deformation of a cable without guying (a) and with guying (b)  
 $P$  Traffic load  
 $G$  Own weight  
 $s^G$  Cable force from own weight  
 $s^P$  Cable force from own weight and traffic load  
 $f$  Deformation  
 $V$  Cable force underspanning  
 This results in:  $f_1 > f_2$ ;  $s_1^G < s_2^G$ ;  
 $s_1^P = s_2^P$ ;  $V_1^P = 0$
- 58 Stress ribbon bridge with guying at the Trift Glacier (CH) 2010, Ingenieurbüro Hans Pfaffen

characteristics. They are very economical structures because the stress ribbon passes over the spans under a constant load and the abutments cost the same as those for single-span stress ribbon bridges (Fig. 54). The individual span loads mean however, that stress ribbons are subject to differing forces. If piers are very stiff, the force is transferred to them and does not influence the adjoining spans. This results in massive, sometimes clumsy looking piers, which have to transfer differential forces via fixed support in the foundation. If the pier is flexible and yields at the top, it transfers force to the adjoining span. This pliability of piers gives rise to greater deformations in the spans, which can be tolerated in pedestrian bridges, in contrast to a gain in force in major bridges. The bridge's fitness for service must not however be impaired, i.e. deformations and accelerations must be limited to a reasonable extent. Stress ribbon bridges can be bent span-by-span in the horizontal section. This bending results in horizontal loads at the height of the stress ribbon, which can be transferred by massive or relieved support structures.

*Deformations, torsion*

While symmetric loads corresponding with the structure's own weight cause moderate deformations, deformation is much greater under asymmetrical loads. The deformations consist of cable elongation and a large inextensible component, like a sagging chain, which reacts to a concentrated load by deforming without an increase in force i.e. inextensibly. Deformation depends on the magnitude of force in the stress ribbon – the higher the tensile force, the slighter the deformation, like a heavy chain, which under the same concentrated load and with the same geometry will deform less than a light one.

*Stiffening*

Stress ribbon bridges have little natural damping so tend to be subject to vertical vibrations. It is therefore advisable to choose a heavier superstructure. Concrete slabs or granite elements are suitable for this purpose, so as to favourably influence the ratio of exciting mass (pedestrians) to the vibrating mass (bridge) – also referred to as the modal mass – and reduce excitability.

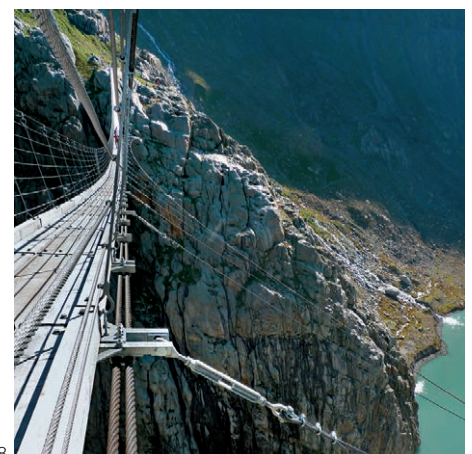
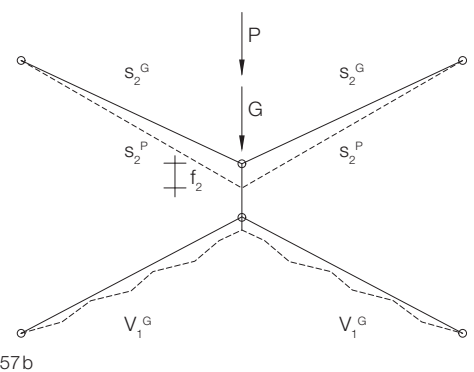
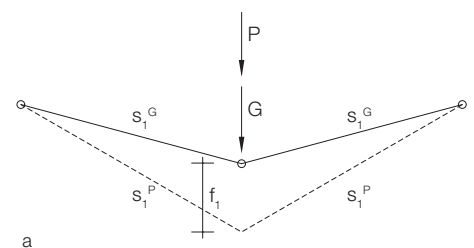
Additive vibration absorbers must in any case not be allowed to impair or destroy a stress ribbon bridge's slender silhouette.

**Cross sections**

There are various ways of combining a walkway slab with a stress ribbon.

*Integrated solution*

In the integrated version, the superstructure itself is designed as a stress ribbon that can absorb tensile forces. While steel and wood are suitable for these structures, concrete requires reinforcement with tendons. Concrete cross sections can be manufactured in stages. Semi pre-cast superstructure segments are first hung on the tendons and then concrete is poured onto them in-situ to form a continuous band. After the concrete has hardened, more tendons are inserted and pre-stressed so that tensile strength is transferred via the pre-stressed concrete cross section. The advantage compared with completely prefabricated slabs is the jointless surface, which avoids the risk of icicles forming under the bridge from dripping water; this is an important consideration in bridges over traffic routes. Pre-stressed steel is manufactured as an endless roll and wound into reels for transport so that it can be installed on site in one piece. Anchoring onto the abutments is carried out using a conventional pre-stressed anchor.





59

If wood or steel is used, superstructure segments can be lifted up in one piece and anchored. If joints outside the bearing area are necessary for transport reasons, a continuous temporary support must be used to ensure that the joint does not have to transfer horizontal forces in joining.

#### *Additive solution*

In an additive or laid solution, concrete or stone superstructure segments are laid on steel bands (Fig. 59). Elastomeric cushioning pads separate the segments so that the plates cannot damage each other if the bridge deforms. They also have a damping effect, which is an advantage in stress ribbon bridges susceptible to dynamic excitation. Steel bands are usually anchored to welded end plates, which are in turn anchored to concrete abutments.

#### *Mixed forms*

Apart from 'true' stress ribbon bridges there are also mixed forms combining features of both stress ribbon and beam bridges. Two types of load transferral can be distinguished here, depending on their stiffness: on the one hand transferral via the superstructure's beam action and on

the other hand via the suspension effect of the stress ribbon. The different ways in which loads are transferred can be illustrated with a thick and a thin band of the same geometry and load. A thick band transfers far more load but low levels of tensile force to its supports when subject to bending, while a thin band has greater tensile force, but transfers less bending force. Targeted pre-stressing can be used to control the distribution of the structure's own weight. Under traffic loads, stresses are transferred in accordance with the prevailing stiffness. Load transfer behaviour can only then be influenced by changing the structure's cross section or geometry.

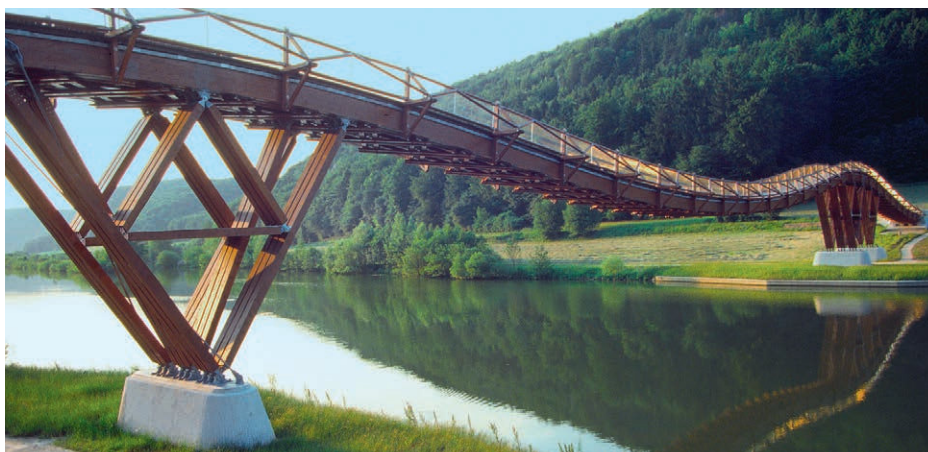
The stress ribbon bridge near Essing in Germany is an example of a combined form (Fig. 60). It was delivered in several pieces, lifted into place and pre-stressed after completion. The supports on both sides of the Main-Danube Canal provide a harmonious transition between the main span and side spans, creating a kind of fixed point, which prevents horizontal displacement of the head, limiting deformation and bending in the superstructure.

Stress ribbons can also be combined with arched support structures. If stress

ribbons are passed over arches, the geometry of the arches can be made to correspond with that of the rolling radius. The arch then takes on the function of a vertical intermediate support; the stress ribbon passes over it and transfers no larger horizontal force to the arch.

Another means of stabilising a bridge is by underspanning, such as that used in the stress ribbon bridge at the Trift Glacier (Fig. 58; see also p. 102f.). From diagonal downward underspanning, the stress ribbon gains not only more weight, but also more force, which increases its stiffness. Under an increasing load, force is successively minimised by underspanning, while in the stress ribbon it increases at only a disproportionately low rate.

When no more force acts on the underspanning, the stress ribbon transfers loads again the usual way with only slight deformations (Fig. 57). Although interesting and very economical structures for long spans can be developed using such systems, very high demands in terms of deformation and slope cannot be made on them. Railings, which contribute to damping through friction, or superstructure plates mounted to increase damping, can often help to improve a bridge's vibration behaviour.



60

The situation is different if the stress ribbon is part of an overhanging system, in which greater forces must be transferred between the angled pillar and the tension member (Fig. 56, p. 56). Forces in the stress ribbon in such systems can only be regulated by using the structure's geometry and own weight. The rise results of itself out of the stress ribbon's own weight and tensile force from the cantilever system. A combination of the compressive (angled pillar) and tensile elements (stress ribbon) balances the

horizontal forces so the ground beneath is subject only to vertical loads, which can be a great advantage.

#### Redirection

The critical points in stress ribbon bridges are the transitions from the stress ribbon to the abutments. Stress ribbons have a very low bending stiffness and tend to be subject to larger deformations, not only under asymmetrical loads, but also due to changes in length resulting from temperature variations, creep and shrinkage.

Particular attention must therefore be paid to the anchoring of the stress ribbon in the abutments and with multi-span bridges to the redirection of the ribbon to the supports. If the stress ribbon warps, the ribbon will buckle at the fixing point, which leads to very large local bending stress due to the great tensile force. To avoid this, the stress ribbon is either passed over a saddle or a haunch is built, which minimises the bending stress from the curvature (Figs. 61 and 62).

Passed over a saddle, the stress ribbon can unroll in a controlled way. By selecting a suitable saddle radius, the bending stress in the band can be controlled. Saddle length will depend on radius; the radius is in turn determined by the ribbon's thickness. The thinner the stress ribbon, the smaller the radius can be and the more compact the saddle. A stress ribbon's cross section must however always be able to absorb the tensile forces imposed. Materials with great tensile strength that can be applied very thinly are particularly appropriate here. Research is being carried out at Berlin's Technical University into the use of high-strength carbon fibre bands less than 1 mm thick for use in stress ribbon bridges (Fig. 15, p. 31).

If there is a haunch, the stress ribbon cross section tapers out successively to

the supports. A haunch is designed with an iterative form so that the load and deformation stresses match the cross section's ability to withstand stress. This solution is not suitable for the additive version however, because here the stress ribbon and walkway are separate from each other. In this case, the stress ribbon is either reinforced by underlying slats, similar to a leaf spring, or equipped with a saddle, which will determine the band's curvature.

#### Load bearing

The foundations of classical stress ribbon bridges must be able to absorb large horizontal forces. Foundation blocks that are anchored in the ground with permanent anchors or micro piles have proven their worth within this context. Both systems can be made with very flat gradients, which help to transfer horizontal forces with as little anchorage force as possible.



59 Stress ribbon, additive solution

60 Combination of a beam and stress ribbon bridge, Bridge over the Main-Danube Canal, Essing (D) 1986, Richard J. Dietrich; Brüninghoff und Rampf

61 Concrete haunch of a stress ribbon bridge

62 Haunch of a stress ribbon bridge with leaf spring 62



63

## Curved bridges

### History

Curved bridges have a relatively short history. Innovative engineers such as the Swiss Robert Maillart experimented in the first half of the 20th century with the properties of freely mouldable concrete and designed the first curved bridges (Fig. 63). After the Second World War, several such bridges with small spans were built, but only in recent decades have engineers attempted suspension or arch structures with larger spans. The rapid development of curved pedestrian bridges began in 1988 with the construction of a suspension bridge over the Rhine-Main-Danube Canal in Kelheim. New software tools and calculation methods have made it possible to attract and establish interest in this new bridge construction genre, with all its functional and structural design potentials. The following section deals mainly with bridges with medium and long spans, because simple curved bridges with closely placed supports fall more into the category of beam bridges and have no major special characteristics.

### Function

In contrast to road and railway bridges, it is possible to choose free forms with curved layouts and tighter radii for pedestrian bridges. Their superstructures can be skilfully adapted to existing route trajectories and terrains, resulting in a very varied range of basic layouts. There is a great scope for individual design, because not only can superstructures be curved, but masts can be tilted, arches slanted and cables angled through space – can and must be – if the equilibrium conditions are to be maintained with reasonable expense and effort. A fluid route trajectory suitable for both pedestrians and cyclists often means that suspended bridge decks can only

be unilaterally supported or hung so as not to breach the clearance gauge. This significantly affects the design however, potentially influencing the choice of a bridge cross section or support conditions.

A distinction is made between two principles in curved bridges: their superstructures are supported either by a primary support structure in the form of a suspension or arch structure, or the primary support structure can be integrated into the superstructure. These two principles are subject to completely different laws of statics.

The superstructure of an external primary support structure is not subjected to any great stress if it is supported on both sides; it can be regarded as a cross section supported on both sides. If a bridge is unilaterally, eccentrically hung however, a so-called 'local carding moment' occurs, which results from the eccentricity between the point from which the superstructure is hung and its centroid. The carding moment must be absorbed by the superstructure's cross section.

If the superstructure is part of the primary support structure, its load-bearing capacity is more like that of a curved beam, which transfers loads through its bending and torsional stiffness. An example of this is curved, bending and torsionally stiff trussed tubes, which are able to transfer torsional moments even over longer spans. Other relieved cross sections such as the one in the Passerelle La Défense in Paris work with clearly separated load-bearing functions (Figs. 67 and 68). Vertical loads are transferred via an outwards tilted truss system consisting of several vertical masts and angled guys.

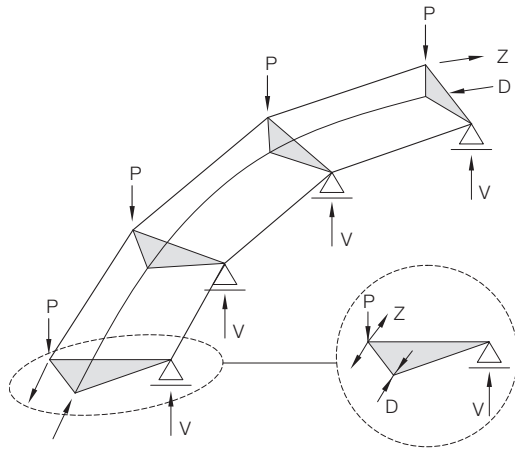
The horizontal forces on the mast heads caused by the curve are transferred via

the vertical stabilisation of the cables to a tension ring below and to the superstructure, are gathered there, then transported to the abutments. Even if the support structure exactly follows the load-bearing behaviour and its geometry is optimised, a steel box girder with high levels of bending and torsional stiffness will still be required for the superstructure if it is to be able to also absorb loads that do not correspond with the structure's geometry.

### Circular ring girders

Circular ring girder bridges with circular and unilaterally hung superstructures are interesting because they very efficiently transfer the expected carding moments. A circular ring girder structure takes advantage of the fact that a slab curved in plan can be kept stable with single supports arranged on one side alone, while a straight slab supported on just one side with one row of supports will tip over. With a straight beam, a torsionally stiff superstructure and a fork bearing are necessary. With a curved beam, it is possible to convert the carding moment into a horizontal force couple and gather the horizontal forces through the ring effect. As with the support cables of a suspension bridge or an arch bridge's compression arch, loads can then be transferred without causing transverse bending. This allows the design's curvature to efficiently compensate for the effects of the eccentric support.

The support system alone will determine which chord tension or pressure occurs in it. If the circular ring girder is externally supported, the lower chord will be subject to tension and the upper chord to pressure; if it is supported on the inside, it is exactly the other way around. The superstructure of the Erzbahnschwinge Bridge in Bochum is hung from the inside from a



64

- 63 Schwandbach Bridge, Hinterfultigen (CH) 1933, Robert Maillart
- 64 Circular ring girder support system. If the tension and pressure rings are positioned one above the other, they can absorb opposing forces (tensile and compressive forces).
- 65 View of a pedestrian bridge, Weiden (D) 1998, Richard J. Dietrich; Heinrich Schröter Ingenieure; no scale
- 66 Curved bridge beam as spatial truss construction made of tubular rods, pedestrian bridge in Weiden
- 67 View, Passerelle La Défense, Paris (F) 2007, Dietmar Feichtinger Architects; schlaich bergemann und partner; no scale
- 68 The 90 metre long curved steel structure is held at the ends by just two support points. Passerelle La Défense

mast, which leads up to a tension ring above, which is integrated into the walkway slab and a compression chord in the form of a tube below (Fig. 71, p. 62). This principle is even clearer in the visitors' bridge in the Deutsches Museum in Munich.

This bridge's superstructure is also a unilaterally supported circular ring girder hung from support cables. The support function is provided by the tension ring under the glass surface, which consists of three steel cables, while the tube below serves as a compression arch. The Liberty Bridge in Greenville, USA is

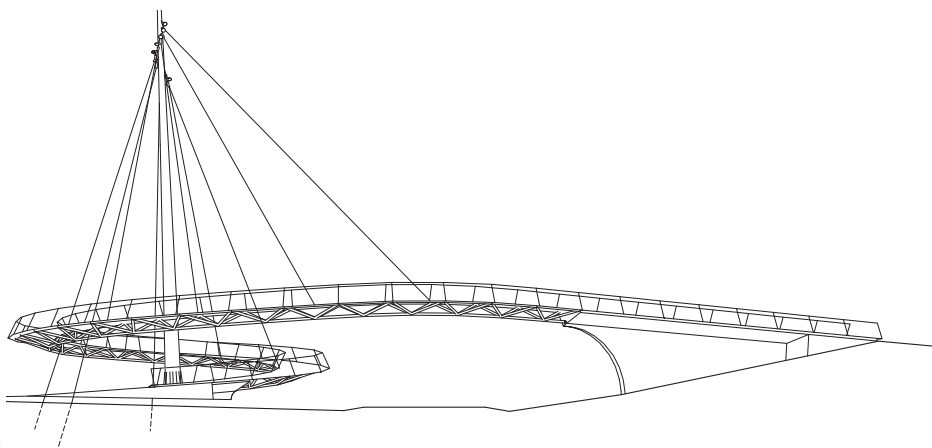
hung externally, so it is subject to tension below and pressure above, which can be clearly seen in the tension ring of three ring cables, which are each redirected on counterforts at intervals of 3.20 m (Fig. 72, p. 62). If a continuous deck like the Liberty Bridge deck is installed, it can be used to optimally absorb the annular compressive force and is also thereby provided with pre-stressing, which will minimise cracking.

*Cable arrangement*

The hanger cables of a unilaterally hung, curved suspension bridge are often tilted,

due to the cable geometry. By shifting the anchorage point it is possible to centre the hanger axis through the superstructure's centroid (Fig. 70, p. 62). In an ideal case, the carding moment, which is defined by the distance of the hanger axis to the centroid, can thereby be eliminated. The superstructure is not subject to any further torsional stress under an even stress load and can therefore be much more slender.

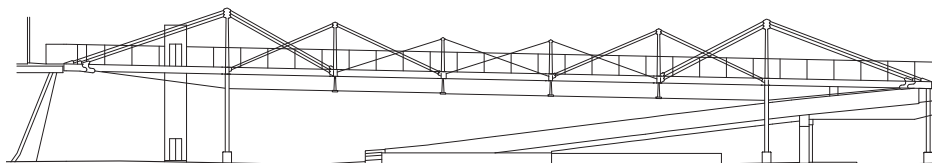
This principle was used in the Seebrücke in Sassnitz (Fig. 69). The hanger cables are fixed to cantilever arms on each side above the walkway and extending



65



66



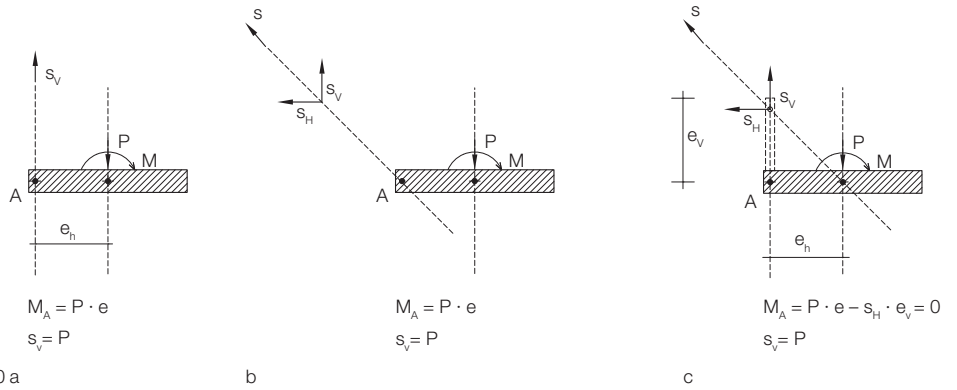
67



68



69



beyond it. The cables are at various heights due to the different hanger angles, so the bridge has its own dynamic. The reduced stress allowed this wing-like superstructure to be built with an extremely slender cross section. A similar superstructure cross section was chosen for the Hafen Grimberg pedestrian and cyclist bridge in Gelsenkirchen, although without the cantilever arm (see p. 108f.). The greater stresses here did however make a somewhat higher steel box girder necessary.

#### Mast

The question of the best site for one or more masts is a very important one with curved suspension bridges. If no functional or topographical constraints indicate specific locations, the mast should stand exactly at the structure's centroid for statics reasons. Only then will the system be in equilibrium and without any bearing reaction at the ends of the superstructure. If the mast is tilted, its foot must be displaced so that the mast's axis passes through the structure's overall centre of gravity. Only in this case will the support cable running up to the mast head and the mast itself form a plane and thus be in equilibrium,

so no guys will be necessary. The extent to which such an ideally balanced mast position is possible and guys can fundamentally be dispensed with will however depend on whether the support cables have a recovery effect, i.e. whether the cables stabilise the mast (Fig. 44, p. 52). This is the case when the mast's foot is positioned under the cables' anchorage points. In this case, guys can be dispensed with, although it must be ensured that no damaging deformations that are too great for the connection details will occur and that the structure is not excessively susceptible to vibration. While it was not possible to dispense with guys in the Seebrücke in Sassnitz due to the large masthead deformations, the deformations in the Erzbahnschwinge Bridge were within an acceptable range, even without guys. Whether or not the mast needs guys depends on many other factors such as the bridge's geometry, its superstructure size and stiffness, and levels of prestressing. Every bridge's support and deformation behaviour must therefore always be individually examined and especially if the bridge has a mast that is not guyed it must be ensured that it is not susceptible to excessive deformations.

#### Load bearing

If the bridge deck is not too wide and the radius of curvature not too large, fully integral solutions may be feasible (Fig. 20, p. 42). The Hafen Grimberg pedestrian and cyclist bridge features such an integral structure with a monolithic anchoring of the superstructure in the abutments. Its steel box girder was fixed with long anchoring elements in the abutment block and can neither warp nor shift.

This support results in complex stresses on the abutments, which usually require deep foundations with piles. If an integral solution is not chosen, as in the case of the Seebrücke, support elements must be provided, which on the one hand ensure that force is absorbed in the supports, but also allow for the deformation due to unspecified degrees of freedom.

#### Curved arch bridges

The boundary conditions for curved arch bridges are very similar to those of suspension bridges. The design of the bridge's cross section in accordance with its stress loads will depend on where the superstructure is supported and whether it is hung or erected within or outside the curve. The cross sections of curved arch



71



72

bridges can be built just like those of a rope bridge, either as compact or as relieved cross sections with a tension ring or compression arch (Fig. 73).

In determining the arch's geometry, the right position for the arch impost must first be found, in a process analogous to positioning a suspension bridge mast. If possible, the resulting net force of the support loads from the arch should be as close as possible to the structure's centroid. This avoids large horizontal stresses in the superstructure and abutments. The ideal arch geometry follows the spatial pressure line, which can be identified by means of a form-finding process. The spatial form is configured to provide equilibrium at every point, i.e. the hangers or pillars and two adjacent arch segments are on the same level. If this ideal form for constant loads can be found, this will be followed by an investigation of the stress occurring as a result of stress loads that do not correspond to the structure's geometry. The resulting bending stress and normal stress from the arch effect will determine the arch's dimensions.

In selecting a cross section, the feasibility of manufacturing its spatial geometry must also be taken into account. Steel tubes are suitable here because of their rotational symmetry. Composite tubes can follow any spatial curve due to their variously angled and axially twisted sections.

Manufacturing elements with square or rectangular steel sections is far more costly and complex, because the arch has to be turned in on itself to follow the three-dimensional curve. If it is to be built of concrete, complicated formwork has to be used and if prefabricated parts are used, additional temporary props are required. Concrete forms also involve an expensive and complicated manufactur-

ing process and larger cross sections, which generally means that freestanding concrete arches are rarely used in pedestrian bridges.

As this excursion into the third dimension has shown, the load-bearing behaviour of curved bridges is more complex than that of straight bridges. The same principle applies to designing these as to all other support systems: global static calculations must be clearly worked out before complex computer calculations are carried out. Planners need suitable calculation software to be able to build such complex support structures and every engineer should be qualified to understand and interpret these computer calculations.

- 69 Anchoring of hanger cables on half frames, Seebrücke, Sassnitz (D) 2007, schlaich bergemann and partners
- 70 Modification of the carding moment by displacing the cable anchorage point
  - a Vertical bearing axis
  - b Tilted bearing axis without displaced suspension point
  - c Tilted bearing axis with displaced suspension point
- P Force [kN]
- M Moment [kN]
- $e_v$  Vertical spacing between anchorage point and centroid [m]
- $e_h$  Horizontal spacing between anchoring point and centroid [m]
- s Cable force [kN]
- 71 Circular ring girder with tension member above, Erzbahnschwinge Bridge, Bochum (D) 2003, schlaich bergemann and partners
- 72 Circular ring girder with tension member below, Liberty Bridge, Greenville/South Carolina (USA) 2004, schlaich bergemann and partners
- 73 Design for a curved arch bridge, Deizisau (D) 2005, schlaich bergemann and partners





## Finishings

Pedestrian bridge finishings include on the one hand structural elements, such as floor surfaces, railings, expansion joints, drainage and bearings and on the other hand, design aspects, such as choice of colour or material. Structure and design are closely interrelated in bridges, especially in their floor surfaces and railings. Furniture and lighting can also underline a bridge's functional-aesthetic aspects and highlight the structure as a whole.

### Surface

The choice of suitable surfaces for pedestrian and cyclists' bridges may be limited or even predetermined by the bridge's structure. A wooden surface will not usually be added to a purely concrete structure, and a glass structure will rarely be topped with a concrete walkway. Some construction materials, however, offer a large degree of design freedom. Steel structures for example, can be effectively combined with concrete, wooden or even glass surfaces.

The following criteria should be taken into account in choosing a suitable surface for a bridge's walkway.

- **Usage:**  
A bridge's principal usage plays a major role in the choice of a suitable deck surface. It must be determined in advance whether the bridge will be used only by pedestrians or will also be crossed by cyclists, horse riders or service vehicles. If the bridge is covered, different deck surfaces to those installed in open structures can be used.
- **Material:**  
In most cases the primary structure, type of usage and economic aspects determine the surfaces' materials, or at least significantly limit the available choices. A reasoned choice of material,

such as local wood or stone, can also lend a bridge a special character.

- **Slip-resistance:**  
The bridge must have a non-slip surface so that it is safe to use, especially if it is directly exposed to weather or its walkway slopes longitudinally. Details on this topic can be found in the German trade association guidelines BGR 181 »Floors in workspaces and working areas that may be slippery« or in the »Guidelines on the slip-resistance of paving and slab surfaces for pedestrian traffic« issued by the German Road and Transportation Research Association.
- **Abrasion-resistance:**  
The deck surfaces of bridges used by cyclists or service vehicles must be resistant to mechanical abrasion.
- **Mass:**  
The mass of the walkway slab influences a bridge's dynamic behaviour. A heavy concrete slab may be advisable for static reasons in some cases to reduce vibration.
- **Transparency:**  
Using glass or metal grating as floor surfaces opens up exciting possibilities and can lend the bridge an extra dimension for those crossing it. Skillful lighting will also highlight the bridge at night.
- **Colour:**  
Thin epoxy-resin based coatings and coloured asphalt or synthetic floorings make it possible to design walkways in almost all shades.

### Concrete

Structures with a concrete walkway don't need any further coating. Their surface must however be roughened with a special broom, given the so-called 'broom finish', to ensure that the surface will have the necessary slip-resistance (Fig. 1, p. 66). The lack of a protective coating

does however make higher demands on the concrete's quality. These requirements are specified in exposure classes, which stipulate the demands on concrete's durability, depending on the possible impacts on it.

Structural problems can occur if a concrete slab, such as a solid deck walkway, which can also improve the structure's dynamic behaviour, is cast on a steel box girder and there must be a watertight connection to the steel structure below. A concrete walkway is therefore usually coated with a thin synthetic coating that provides slip-resistance, protection for the concrete, sealing and even a range of colours.

### Steel/aluminium

Metallic surfaces such as those of orthotropic plates or box girders can be used without additional coatings (Fig. 2, p. 66). It must be taken into account however, that slip resistance can be ensured by appropriate metal sheeting, such as perforated or grooved plates, or metal grating, although the corrosion protection usually wears off due to mechanical abrasion.

Using stainless steels, weatherproof steels or aluminium can reduce wear, but these metals are not used in most cases because they are too expensive. Adding a thin synthetic coating to a metallic surface provides a non-slip surface while also preventing damage to its corrosion protection.



#### Thin synthetic coatings

Synthetic resin-based coatings seal and protect steel and concrete surfaces. In Germany the use of such coatings on concrete surfaces is regulated by the Federal Highway Research Institute (Bundesanstalt für Straßenwesen – BAST) (surface protection systems) in its »Additional technical regulations and guidelines for civil engineering structures« (ZTV-ING) standard, in »Part 3: Solid structures, Chapter 4: Protection and maintenance of Concrete structures«. For use of thin coatings on steel surfaces, »ZTV-ING, Section 7 Part 7: Bridge surfaces – Chapter 5, Synthetic resin-based coatings on steel« applies. Synthetic coatings usually consist of three layers: a base coat, a mainly effective protective layer and deck sealing, and are approximately 4–5 mm thick. Applying a layer of quartz sand provides a non-slip surface. Surfaces can be made in almost all shades, providing colourful highlights. Light-coloured surfaces are however susceptible to dirt and visible skid marks, from bicycles for example. To avoid spalling or large flaws, demands on the substructure, such as the adhesion of concrete and environmental conditions such as humidity and temperature must be taken into account in the concrete's manufacture.



#### Asphalt

(Mastic) asphalt deck surfaces are poured onto concrete and steel substructures (Fig. 4). Bitumen is mainly used as a sealant, cf. »ZTV-ING Part 7: Bridge surfaces, Chapters 1–4. The overall thickness is usually 8 cm consisting of a 0.5 cm sealing layer, a 3.5 cm protective layer and a 4 cm deck layer. An overall thickness of 4–5 cm can also be applied in some cases. Such surfaces do significantly increase the structure's weight, which can be a disadvantage,

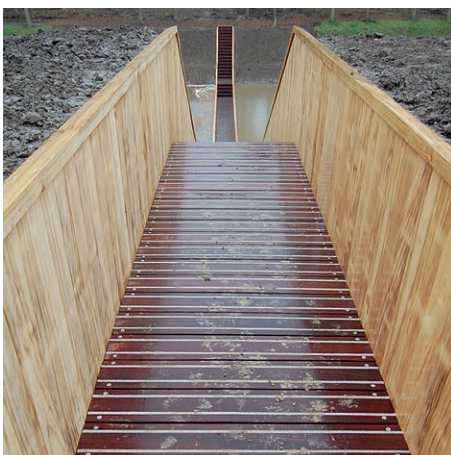
especially for light-weight bridges. As with synthetic coatings, (mastic) asphalt surfaces can be stained to provide colour highlights. Attention should be paid to the fact that mastic asphalt has an installation temperature of approx. 180–220 °C. The impact of such a high temperature on the structure as a whole when the asphalt is poured can therefore be a design-relevant loading condition.

#### Wood

Wooden elements, especially if they are exposed to weather, must be ventilated on all sides preferably to avoid mould formation or rotting (structural wood protection). This is a precondition for the use of wooden surfaces and means that wood is usually only used for bridge surfaces in open structures such as girder grids or trussed girders. Joint details must be carefully planned to avoid badly ventilated details or areas under standing water.

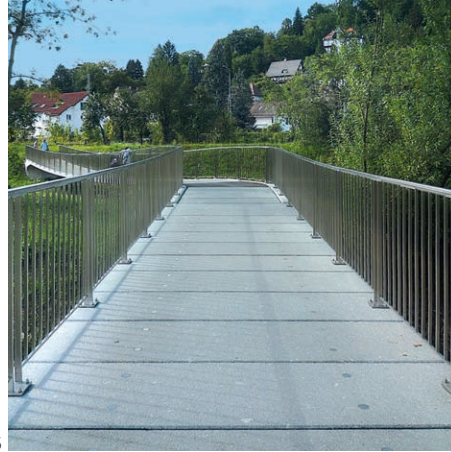
When designing wooden elements, the maximum available dimensions and usage must be taken into account. Longitudinal planks may pose a danger to cyclists and inline skaters because they could cause them to fall if their wheels get caught in the gap. The comparative slipperiness of wet wood must also be considered, especially with weathered and sloping surfaces. It is advisable in any case to lay planks across the grain. Additional anti-slip measures may also be necessary. The surface can for example be grooved in strips with additional epoxy-resin filling scattered with quartz sand (Fig. 3).

Wood changes colour during its natural ageing process, which can enliven a structure and a bridge's appearance.





4



5



6

### Glass

Glass surfaces can provide a unique perspective and sense of space, in bridging a ravine for example, and a transparent surface highlights a structure's lightness (Fig. 7). A glass walkway can also be lit up with appropriately placed lighting, providing additional design highlights.

The construction of such glass walkways in Germany must be approved in each case by the "Center of competence in civil engineering" (DIBt) in Berlin. As well as performing impact tests, the DIBt comprehensively tests structure's residual strength. These tests guarantee that the crack of a single layer does not cause the failure of the pane or its anchorage as a whole. The decision to use a glass surface can however already affect the primary structure at the design stage as glass panes allow for only slight local differential deformations and they must be able to be replaced easily. It must also be ensured that the surface has the necessary non-slip properties, especially if it is a sloping or weathered surface.

### Natural stone

The use of stone as a deck surface can, like wood, lend a bridge a special design character (Fig. 5). A careful choice of stone in an urban development or historical context can help establish a structure in its location. Conventional laying of stone in a mortar bed is however not advisable for light and dynamic structures, because deformations of the bridge under wind or traffic loads will damage the surface's impermeability. No such restrictions apply if open gaps are used, but in this case the drainage of the surface must be precisely considered. Installing a second drainage layer under a stone surface makes the structure more complex to maintain. Direct drainage through the structure's joints may be possible in some cases, but not if de-icing salts are used in winter or there is a danger of icicles forming and falling from the gaps.

### Synthetics

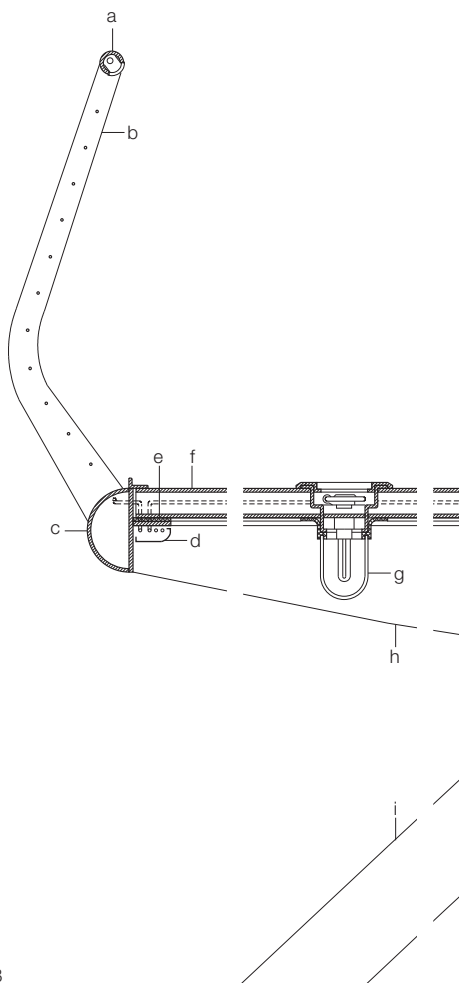
Synthetic surfaces are usually found at athletics sport facilities. They are also used on pedestrian bridge decks in some cases and dyeing them can open

up additional design possibilities (Fig. 6). Such surfaces generally consist of two layers; a rubber granulate elastic layer and a top layer of EPDM granulate, as well as a polyurethane bonding agent. This flexible surface defines the experience of walking on the bridge for people crossing it – a factor that must be intended and be appropriate to the individual structure.



7

- 1 Concrete surface with broom finish, Alfenz Bridge, Lorüns (A) 2011, Marte.Marte Architects; H + G Engineers
- 2 Metallic surface, pedestrian bridge, Hotton (NL) 2002, Ney + Partners
- 3 Wooden deck with quartz sand surface, Laufgraben Bridge, Brabant (NL) 2011, RO&AD Architects; H.E. Lüning
- 4 Asphalt surface, Nordbahnhof Bridge, Stuttgart (D) 1993, Planungsgruppe Luz, Lohrer, Egenhofer, Schlaich
- 5 Stone slab surface, Fehrlesteg bridge, Schwäbisch Gmünd (D) 2011, schlaich bergemann and partners
- 6 Plastic surface, »Slinky springs to fame« bridge sculpture, Oberhausen (D) 2011, schlaich bergemann and partners with Tobias Rehberger (artist)
- 7 Glass bridge deck, Quarto Ponte over the Canale Grande, Venice (I) 2008, Santiago Calatrava



### Railings

Railings on bridges serve primarily to protect people from falling, so they are an essential component of every pedestrian bridge. Because they are not usually part of the primary structure, they can be reduced as far as possible so as not to detract from a bridge's appearance and from the perception of the supporting structure. The design of railings should take both structural and constructive aspects into consideration:

- Horizontal load, also called capping load, is set in Germany at 0.8 kN/m on the railing's upper edge.
- The distance between adjacent elements must be no more than 120 mm to prevent children from getting their heads stuck between individual structural elements.
- If cross bars are horizontal, people must be prevented from climbing on them. This can be ensured by an additional inward-sloping handrail on the inside of the walkway or by tilting the railing inwards towards the bridge.
- The railing height must be set based on the type of usage. If cyclists or horse riders use the bridge, the parapet should be higher than it would be on a footbridge exclusively for pedestrians. If the bridge's fall height is very high, i.e. its deck is a long way above the ground, it will need a higher railing to increase the users' feeling of safety.
- Rigid continuous railing elements should have expansion joints at regular intervals to prevent secondary stresses due to changes in temperature.

Design and functional factors must also be considered in choosing suitable railings, too.

The transparency of railings in particular has a major influence on a bridge's overall appearance. A well-shaped handrail can invite people to lean on it and linger,

it can even have integrated illumination to highlight the bridge at night. In designing railings however, the most important thing is that the individual elements and the railing as a whole have the right proportions. Railings should not be regarded as a necessary evil that detract from the look of the structure, but rather as an integral, if not integrated component of the bridge.

Some types of railing and their special characteristics are described below.

### Vertical bars

A railing with vertical bars set at a maximum clear distance of 120 mm is the most common form of railing. The main focus in planning this type of railing is on reducing the cross section, designing connection details and integrating the handrail.

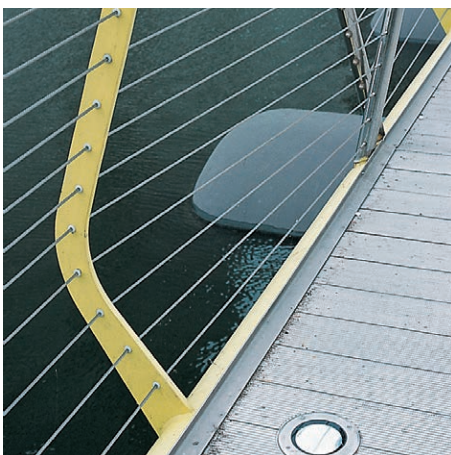
### Horizontal cross bars

People can be prevented from climbing horizontal cross bars by an additional inward-sloping handrail or by tilting the entire railing inwards (Figs. 8 and 9). Alternatively, the lower section of the railing up to a height of 60 cm can receive a closed, flat surface or the lower bearing bars can be arranged at a distance that a child's foot cannot fit between them. The clear distance here must be less than 2 cm, although this can detract from the structure's transparency. Consistently applied, this type of railing visually accentuates the structure's direction.

### Stainless steel cable mesh railings

Highly transparent railings can be realised using stainless steel cable mesh. The cables are approximately 1.5–2.0 mm in diameter and are clamped to form diamond shapes. To effectively prevent people from climbing the railing, the mesh size must be selected so that a child's foot

8



9



10

of  $60 \times 40$  mm cannot fit into the mesh. A distinction is made between vertical and horizontal meshes. Vertical meshes allow for larger mesh sizes, even with the same requirements to protect people from climbing on them, but accentuate the structure's verticality and create greater transparency. Cable mesh must be pre-stressed to ensure that it has the necessary stiffness equivalent to the plane. The prestressing force is up to  $0.5 \text{ kN/m}$  in both directions. If cables are used as a border instead of rigid edge beams and if the edge cable has a sag of approximately  $30 \text{ mm}$ , the posts can be arranged at a distance of approximately  $3 \text{ m}$ . If rigid edge beams are used, the distance between the posts can be freely chosen, although the edge beams and railing posts have to have appropriate dimensions.

The edge cables or beams of cable mesh railings are also made, logically, of stainless steel, because if they were made of other materials the corrosion protection would be damaged by friction from the cable mesh.

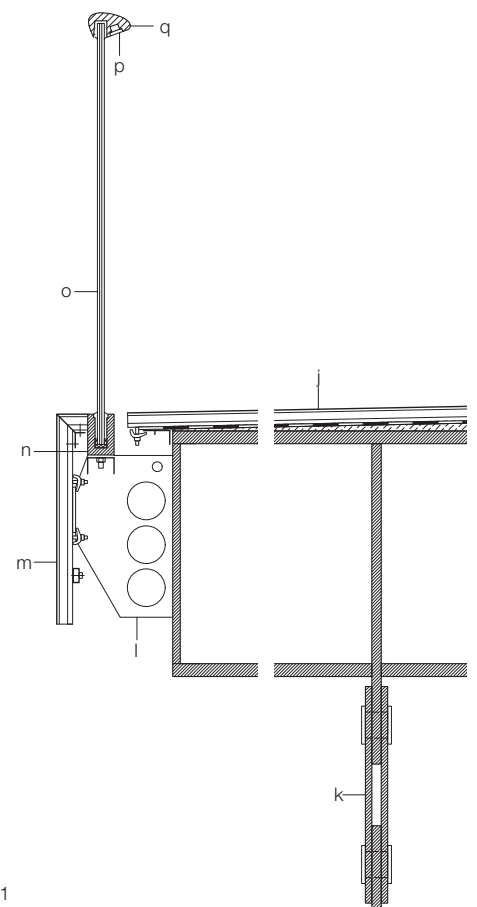
While the intermediate posts only take horizontal forces transverse to the walking direction, the end posts have to take

additional loads from anchoring the pre-stressed rope cables. They are anchored either to rigid end posts by back anchoring with deflection of the upper edge rope or by an inwards-sloping support with a pressure bar. In all three cases, the posts are subjected to much higher stresses, so their cross sections must be larger or must be reinforced.

One great advantage of cable meshes is that they are very flexible at the mesh level and also vertically. This means that bending routes, curves and turns can be very well executed with a continuous railing. They are also vandal-proof.

#### Chain link railings

A (stainless steel) chain link railing creates a structure resembling a cable mesh and also looks similar. Chain link railings are more cost-effective but do not have the fine detailing of cable mesh. The meshes are always quadratic and cannot absorb bends at the mesh level – a disadvantage compared with more flexible cable meshes. There is also a risk that the wires' greater stiffness will mean that any deformations that do occur, such as from wanton kicking, will remain visible in the form of bulging.

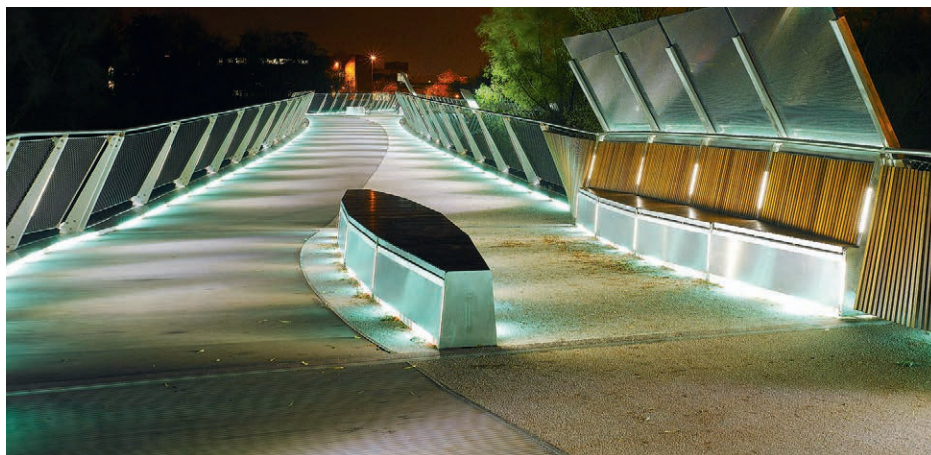


11

- 8 Vertical section, pedestrian bridge, West India Dock, London (GB) 1996, Future Systems; Anthony Hunt Associates, Scale 1:20
  - a Handrail, stainless steel tubing  $\varnothing 60.3 \text{ mm}$  with integrated lighting
  - b Flat steel railings  $60-120/15 \text{ mm}$  with steel cable, stainless steel  $\varnothing 6 \text{ mm}$
  - c Steel tube  $\varnothing 219 \text{ mm}$  halved and welded with flat steel,  $220/12 \text{ mm}$
  - d Electric cable channel, stainless steel
  - e Intermediate layer, EPDM,  $5 \text{ mm}$
  - f Extruded aluminium profile deck planks with closed chambers and integrated cable conduit
  - g Integrated deck lights
  - h Steel angle  $139-425/125/12 \text{ mm}$
  - i Steel tube  $\varnothing 225 \text{ mm}$
- 9 Horizontal stainless steel cable filled-rod railing, pedestrian bridge, West India Dock
- 10 Railing as part of the primary structure, pedestrian bridge, Stahille (B) 2004, Ney + Partners
- 11 Vertical section, bridge memorial, Rijeka (CR) 2004, 3LHD arhitekti; C.E.S. Civil Engineering Solutions. Scale 1:20
  - j Floor surface: profiled metal sheet, aluminium, anodized, ribbed  $202/40/3.5 \text{ mm}$ , sealed sheeting plastic, epoxy tar  $5-30 \text{ mm}$
  - k Tension bearing, steel joint  $6 \times 575/15 \text{ mm}$
  - l Blade with pipe guide, flat steel  $10 \text{ mm}$
  - m Revetment, profiled metal sheet Aluminium, anodized, ribbed  $40 \text{ mm}$
  - n Aluminium profile LJ  $75/120 \text{ mm}$
  - o Balustrade, ESG,  $19 \text{ mm}$ , PVC coating
  - p Covered LED strips, epoxy resin
  - q Handrail, teak  $112/60 \text{ mm}$
- 12 Glass railing, bridge memorial



12



13

13 Seating on a bridge, Living Bridge, Limerick (GB) 2007, Wilkinson Eyre Architects; Arup

### Glass railings

Glass railings offer further opportunities for reducing a railing's visual impact on the support structure to a minimum, of making a bridge appear as slender as possible, and of giving users a feeling of maximum transparency (Figs. 11 and 12). If a bridge does not need any railings at all and the glass surface reflects only slightly, users can even be given the impression that they are moving through open space.

Glass railings are made of at least two panes of laminated glass with a composite film between them. In designing them and determining their size, the relevant codes, »Technical Rules for the use of accident-proof glazing« (TRAV) and »Technical Rules for the use of glazing on linear supports« in Germany (TRLV), which are issued by the DIBt, must be observed. Approval will also usually be required in each individual case.

### Integrated railings

In some cases, a bridge's design will make it possible to integrate railings as an essential component of the primary structure into the overall support structure. The upper chord of a beam or trough bridge with a small span can function as a handrail, while railings with countless small openings will give the bridge an appearance of permeability (Fig. 10, p. 69).

If the hanger cables of rope and arch bridges are regularly positioned, it may even be possible to dispense with railing posts entirely. In this case, the railing's edge rope must be securely connected to the bridge's bearer cables and it must be ensured that the horizontal force resulting from the flexibility of the hanger cables does not produce excessive deformations. There is only a slight risk that this will overload the hanger cables.

### Handrails

A bridge's handrail is a particularly important component. As well as having functional, static and structural aspects, properties such as proportion and materials will influence a bridge's usage and appearance. The height of the handrail, in accordance with ergonomic findings, should not be over 1.10 m. If railings are higher, it is advisable to install an extra handrail at a height of 85–90 cm.

In its most reduced form, as an edge rope in a cable mesh or chain link railing, a handrail contributes greatly to a bridge's transparency. An all-glass handrail that seems to 'disappear' can give users a feeling of freedom of movement. A handrail with an appropriate form and size can also enhance a lookout point, inviting people to rest their arms on it and take in the view of the landscape or surrounding area.

An additional inward-sloping handrail is purely functional, in that it provides the necessary protection against people climbing on the structure and if the walkway slopes, it also allows people whose mobility is impaired to use the bridge without restriction. A handrail can also carry integrated lighting, discreetly and effectively illuminating the walkway and highlighting the bridge at night.

### Furniture

Equipping a bridge with seating can highlight individual areas (Fig. 13). Benches, which can also be integrated into the structure, invite users to linger or enjoy the view. Creating various deck surfaces or different walkway levels can help to further accentuate these areas and emphasize the deck's separation into paths for cyclists and for pedestrians. Plantings on bridges may be desirable in some cases to protect users from un-

wanted external influences such as traffic noise. Added fittings sometimes also very pragmatically fulfil an essential purpose, serving for example as shockproof protection from overhead wiring if the bridge crosses an electrified railway line.

### Expansion joints

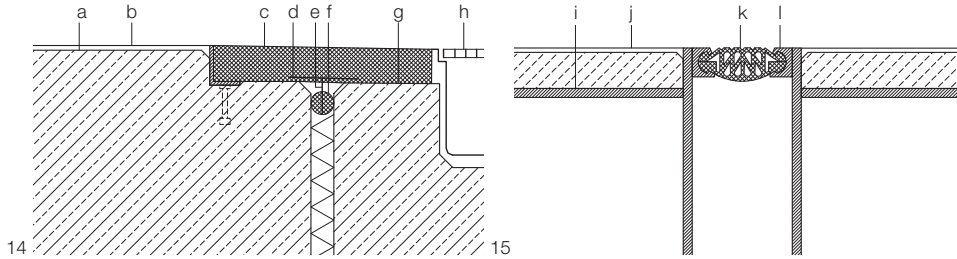
Depending on expansion lengths and the bridge's static system, its abutments may have to absorb large displacement paths. Expansion joints and transitions to the deck are, like bridge bearings, structural elements requiring high maintenance, so the option of an integral structure should be examined in the interests of ensuring the bridge's durability and robustness.

### Integral structures without expansion joints

In an integral structure, the superstructure is monolithically integrated into the substructure, i.e. the abutments or piers. Longitudinal deformations resulting from changes in temperature are largely absorbed by internal indirect stresses – in curved bridges by radial deformations, which shortens displacement paths to the abutments in a longitudinal direction. At best, it may be possible to dispense with expansion joints altogether.

### Expansion joints for small expansion distances

If expansion distances to the abutments exceed approximately 5 mm, expansion joints should be installed, even in integral structures. For small expansion joints of up to 10 mm, small expansion joints from various manufacturers can be built in (Fig. 15), and for expansion distances up to 30 mm, practically maintenance-free bitumen transitions to the deck in accordance with the German civil engineering standard »ZTV-ING, Part 8: Structural equipment, Chapter 2, Asphalt carriageway transitions« are used (Fig. 14).



**Expansion joints for large expansion distances**

If the expansion distances are larger, the transition between the bridge and the deck should be planned with great care because expansion joints cannot normally be used here due to the increased space they require. It is usually difficult to connect transition constructions with overall heights of up to 40 cm with the height of the walkway slab. A project-specific solution should be found in such cases, with cover plates absorbing the deformations, for example (Figs. 16 and 17).

**Drainage**

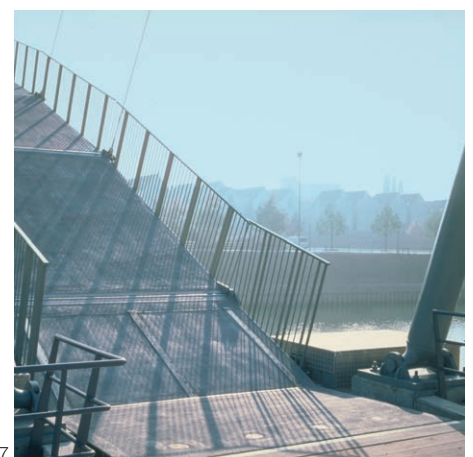
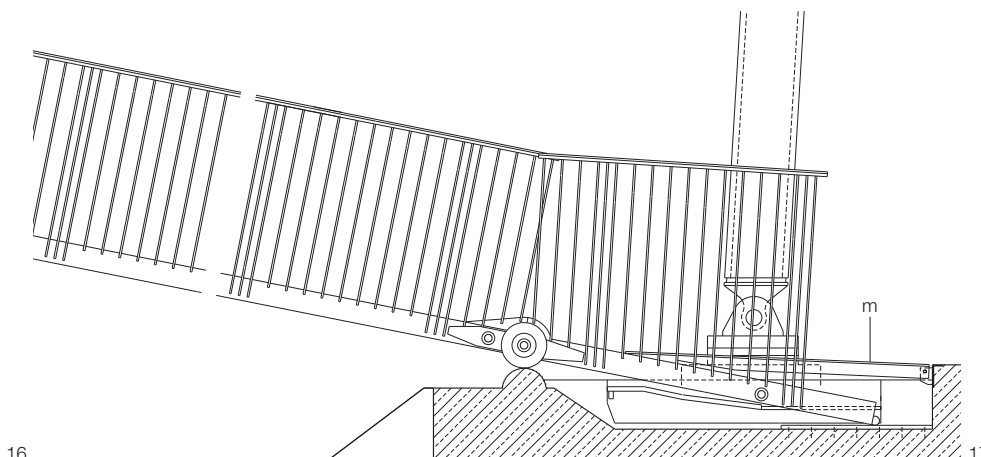
To ensure proper drainage on an open bridge, its walkway must have a minimum slope in a longitudinal and a transverse direction.

If a bridge does not already have a planned gradient, its slope should not be less than 2% in a longitudinal direction. It must also be taken into account that creep deformations in straight concrete superstructures can negatively affect their gradients. The superstructure must therefore be manufactured with a camber that will compensate for the expected deformations by modifying the structure's geometry in advance during the manufacturing process.

A gradient of approximately 1.5–2.5% in a transverse direction is required. To keep rainwater from collecting on the usually structurally complex edge details, such as the transition between a deck surface and a side plate, a V-shaped slope with a flow channel in the middle of the bridge can be used for narrow superstructures up to 3.50 m wide. On wider superstructures, it may be advisable to incorporate a W-shaped transverse crossfall because this will keep water away from critical edge areas and the main traffic area, usually the middle of the walkway.

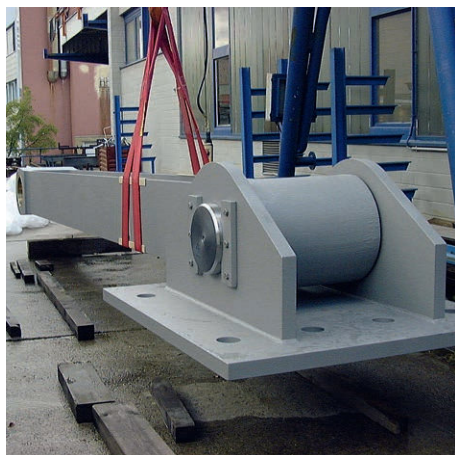
There are several ways of draining surface water from a bridge. One simple and inexpensive solution is to mount box gutters behind the abutments at the transition between the bridge and the path. This dispenses with the need to penetrate the structure, which can be complicated. Otherwise, drainage may have to be integrated into the walkway or even the superstructure. This solution's feasibility will depend on the drainage lengths and amounts of water involved, but the aim should always be to implement this type of solution, even in critical drainage conditions. Installing transverse drains or inflows in or near the super-

- 14 Expansion joint for medium expansion distances up to 30 mm
  - a Reinforced concrete abutment
  - b Thin film surface
  - c Bitumen transition to the deck
  - d Masking strips
  - e Fixing pin
  - f Underfill
  - g Strip foundation, reinforced concrete
  - h Drainage channel, steel profile
- 15 Expansion joint for small expansion distances up to 10 mm
  - i Superstructure, box girder, steel
  - j Thin film surface
  - k Neoprene profile expansion joint
  - l Edge profile, steel
- 16 Transition construction for large displacement paths, lift bridge, Innenhafen Duisburg (D) 1999, schlaich, bergemann and partners
- 17 Lift bridge, Innenhafen Duisburg



16

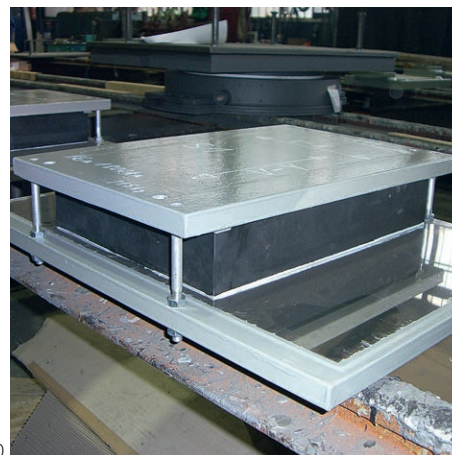
17



18



19



20

structure always involves complex and correspondingly expensive joint details. Drainpipes under the superstructure are also usually unacceptable for design reasons, unless they can be made almost invisible and hidden in the cross section, while remaining accessible.

Integrated direct drainage through downpipes can only be installed at the superstructure's intermediate supports. An economical alternative to this that may also be acceptable in design terms is direct drainage from waterspouts. Authorities will however only rarely approve this method, because uncontrolled drainage is usually prohibited, especially for inner-city bridges, due to the use of de-icing salt in winter.

### Bearings

Bearings are usually used wherever superstructures or supporting structural elements require a tension-free connection to substructures. Bearings must friction-lock two adjoining structural elements to each other and absorb displacements and/or torsion with as little tension as possible. Depending on the required flexibility and degree of freedom, bearings can be fixed or movable in one or many directions. Since a bridge structure usually has a definite longitudinal or transverse direction, degrees of freedom can be required in a longitudinal or transverse direction and in combinations of the two.

Classic bearing types such as spherical or sliding bearings are, like expansion joints, particularly high-maintenance special components. Planners should therefore give preference to integral structures as they are largely maintenance-free.

Conventional bearings are now very reliable and approved for use by building authorities, but can often seem too obvious. For this reason it is advisable, especially with filigree pedestrian bridges, to consider other bearing constructions that

are more satisfactory from a design point of view. As well as classic forms of bearings, some other types of bearings used in pedestrian bridge construction are described below.

### Pendulum bearings

A (tensile) compressive pendulum forms a solid joint appropriate for steel construction between the superstructure, supports and foundations (Fig. 18). A bolted connection forms a movable joint, which can move between adjacent structural elements due to the pendulum's rotation. The dimensions of bolts and brackets will be based on current steel construction standards. Quenched and tempered steel 34CrNiMo6V is a suitable material for bolts and meets high demands in terms of strength and ductility, although approval may be required in each individual case.

Bolted joints are also used in cable and tension and compression rod anchorings. In this context, their dimensions, materials and corrosion protection are integral parts of officially approved tension elements.

If movability in several directions is required, a bolted joint can be combined with pivot bearings.

### Point rocker bearings and ball bearings

Fixed, movable bearings can also be manufactured to comply with steel construction standards. They can absorb angle displacements and allow the bearing to tilt through any axis. With an appropriate calculation procedure (Hertzian contact stress) and the help of the rotational kinematics of cylindrical or spherical bodies, the flux of force can be clearly and compactly represented. To absorb horizontal forces and secure the position it is advisable to install thrust dowels, which fit precisely into openings and prevent displacement.

### Classic bearings

Spherical, pivoted or sliding bearings are examples of classic bearings with slide pairings. This type of bearing transfers vertical forces into the bridge's substructure and consists of a sliding plastic, e.g. PTFE, and (stainless) steel bearing base (Fig. 19). These bearings must be inspected at regular intervals and replaced if necessary.

These structural elements are more functional than aesthetically satisfying in most cases, so they are better placed in »hidden« joints, such as in the abutments.

### Elastomeric bearings

Reinforced elastomeric bearings are made of special raw rubber compounds. During the manufacturing process and vulcanising, the elastomer is provided with high-strength steel reinforcement, which ensures the necessary stiffness. The bearing can absorb torsion through compressive strain and expansion and horizontal displacements through shear deformation (Fig. 20). The bearings' strength and existing deformations should therefore be taken into account in the dimensions of elastomeric bearings. Larger displacements can be absorbed through combination with an additional sliding surface.

Such bearings are usually less expensive and more robust than classic bearings with slide pairings, although they may still need to be replaced. Elastomeric bearings are less suitable for use in highly visible joints because of their block-like appearance.

### Lighting

Pedestrian bridges are usually used not only by day, but also at night or during twilight. A bridge's lighting must therefore be taken into account at an early stage of planning. Lighting is either pro-



21



22

vided indirectly in the form of ambient light or directly by light sources integrated into or placed on the bridge.

A bridge's lighting must fulfill three main tasks:

- Lighting the walkway to ensure safe use of the bridge
- Illuminating the immediate environment, so that oncoming users can be recognised in good time, increasing peoples' subjective feeling of safety.
- Highlighting the structure at night to accentuate its shape and support structure and to call attention to it as part of a specific local identity within an urban planning context (Figs. 21 and 22).

Planning a lighting concept is a highly complex task that should be carried out by a qualified lighting designer. The type of lighting, intensity of illumination, the integration of lighting into the structure, its power supply and any colour concepts all play an important role here. Some major aspects and issues in the lighting of a bridge are outlined below.

Lighting planning is based on the German DIN EN 13201 »Street lighting«

standard. The standard divides structures into lighting classes in accordance with the quantity and speed of road or path users, an analysis of potential hazards, and the intensity of ambient illumination.

Lighting classes are defined by a series of photometric specifications such as luminance, intensity of illumination, the light's evenness, glare limitation and colour reproduction.

In Germany planners work with the S-classes S1–S7 and an assessment of the horizontal intensity of illumination. In other European countries, this assessment is made using the hemispherical luminance and the A-classes A1–A6. The lighting levels of the S and A classes are comparable, S2 with A1, S3 with A2 etc. Classes S7 or A6 at the end of the scale are lighting classes with indeterminate specifications, i.e. there are no minimum requirements on the lighting of bridges.

The ES classes ES1–ES9 can be used as additional classes for pedestrian areas if it is important to be able to identify people or objects, especially in areas with high crime rates. They assess the semi-cylindrical intensity of illumination  $E_{hz}$ ,

measured in lux. EV classes EV1–EV6 also help to assess these criteria. They apply in situations in which vertical surfaces, such as the safety fencing of a cycle path for example, need to be highly visible.

**Lighting of the deck surface**

Its lighting must illuminate the bridge's deck so that users can cross the bridge safely and quickly.

The actual perception of the structure and its environment – and thus the clarity of the route and subjective feeling of safety – is determined by the intensity of illumination  $E$ , which is measured in lux, and the luminance  $L$ , which is measured in candela/m<sup>2</sup>. While the intensity of illumination measures the light output hitting a surface, luminance describes the light issuing from a surface. Luminance is also the measure of the impression of brightness that the eye has of a luminous or illuminated surface.

If for example a higher level of lighting is desired for a bridge, more or stronger lights can be used to increase the intensity of illumination. Alternatively, the surface's reflective properties – especially if it is very dark – can be improved by the installation of a lighter deck with better

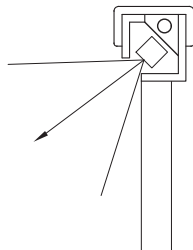
- 18 Pendulum bearing
- 19 Spherical bearings transfer vertical forces into the bridge's substructure and absorb rotations via a spherical calotte and a concave bearing base.
- 20 Elastomeric bearings can absorb vertical loads, horizontal displacements and torsion through all axes.
- 21 Bridge without lighting, bridge sculpture »Slinky springs to fame«, Oberhausen (D) 2011, schlaich bergemann and partners with Tobias Rehberger (artist)
- 22 Bridge with illuminated handrail and integrated lighting from below, »Slinky springs to fame« bridge sculpture
- 23 Highlighting at night, Aaresteg Mülimatt, Windisch (CH) 2010, Conzett Bronzini Gartmann

23

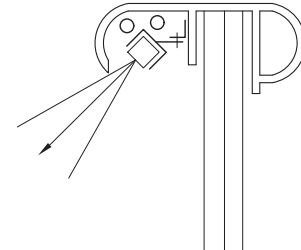




24



25 a



b

reflective properties, which will increase its brightness. Even lighting is another important aspect in bridge illumination. On the one hand, the human eye takes a long time to adapt to big differences in brightness; on the other hand, this means that potential dangers in dark areas will not be seen or only seen with difficulty.

A further disruption to perception is caused by glare. Depending on the glare's intensity, it can reduce visual comfort or even lead to a complete inability to see. If a bridge crosses a traffic route it must be ensured that traffic passing below (shipping, cars, trains) is not negatively affected by its lighting, either by directing the light or taking appropriate anti-glare measures.

#### Adapting luminance

A bridge's luminance should be adapted to its users and the surrounding area. Adaptation to the ambient light is required to avoid great differences in luminance. Objects or buildings close to the bridge in particular must be taken into account in planning lighting.

In an inner-city area, adapting the bridge's lighting levels to the surrounding area may sometimes require levels of luminance well in excess of the specifications of DIN EN 13201. In a natural setting in contrast, a bridge's lighting, taking the surrounding area into account, may be reduced to orientational lights to provide visual guidance. Or the bridge itself could be completely unlit, with floodlit trees or art works marking the way at its beginning and end, exercising a perceptible visual attraction, even from far away. In this context, it must be decided whether the bridge's lighting is designed to achieve an architectonic or artistic effect. Coloured highlights can also give a bridge an orientational or representative function.

#### Illuminants, lights and their mounting

The choice of lights will depend primarily on the lighting's purpose and the effect it aims to achieve. Extensively radiant light can provide evenly diffused illumination, or lighting can be high-contrast, with targeted, selectively placed spots (Fig. 23, p. 73). Lights, through their dimensions, form, and positioning as integrated or independent elements, also influence perceptions of the bridge as an architectonic whole.

Protection from the weather and/or vandalism should also be taken into account in planning and may limit the choice of suitable illuminants. Last but not least, technical factors such as investment and maintenance costs or forecast service life may be further criteria in the choice of lights and illuminants.

For lighting pedestrian bridges, illuminants are chosen that will render colours well and produce a pleasant ambience in a warm white tone. Halogen metal halide lamps, which provide brilliant light with fewer fluorescent lamps as well as a uniform light, are particularly suitable for this purpose. LEDs, which can be combined to form modules as floodlights, linear bands or spotlights, are also increasingly being used. Their advantages lie in their minimal dimensions, long service life, energy efficiency, good dimmability and excellent operational performance at cool temperatures.

The illumination they provide is homogenous and sharply defined without diffused light. The lighting colour can be freely chosen and range from warm white through cold white up to coloured lights. Because of their small size, LED lamps can be unobtrusively integrated into the structure and with appropriate management, a very diverse range of lighting scenarios can be developed and created.

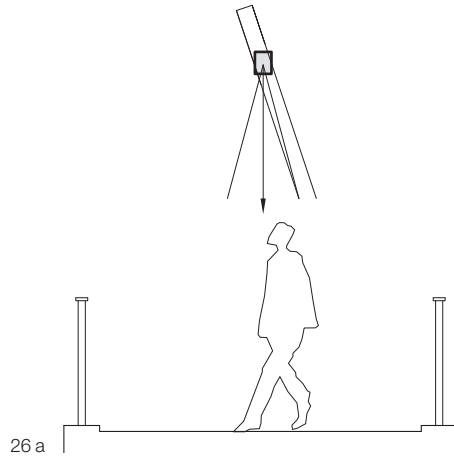
#### Choosing lights

A light consists of an illuminant, a reflector and casing. Their range is enormous; a selection of suitable lights is listed below:

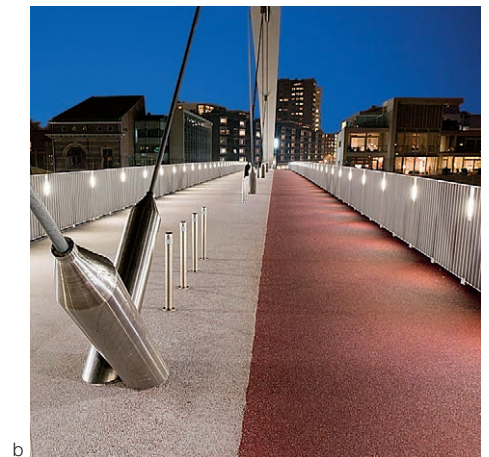
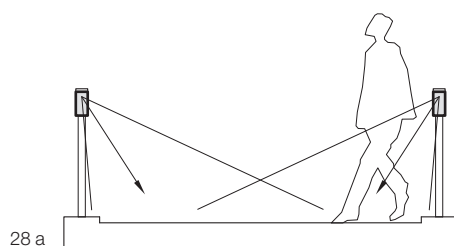
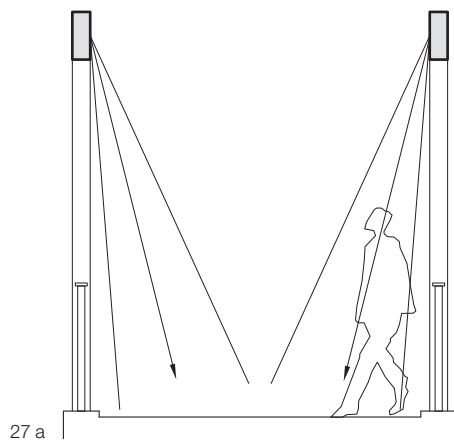
- Handrail lighting (Figs. 24 and 25): Integrating lighting elements into handrails allows lighting to be designed in many diverse ways. Fluorescent tubes or LED bar-shaped lights are generally used for this purpose. Because a handrail is a functional element in constant contact with passing users, particular care must be taken to protect lights from vandalism.
- Floodlights and spotlights (Fig. 26): A bridge's structure can be used to integrate floodlights into tall masts or pylons or on a cable-stayed or suspension bridge. Arch bridges can be especially effectively highlighted by an illumination of their arch. Walkways are often lit from a great height so that they are extensively and evenly illuminated.
- Pillar lights (Fig. 27): Various manufacturers make modular pillar lights that provide varying points of light at different heights and diverse distributions of light. While these lights blend into the structure as simple stelae by day, at night they provide a targeted illumination of the walkway. The principle in installing these is, the lower the point of light, the shorter the distance to the next light should be.
- Orientation lights (Fig. 28 and 29): Bands of light integrated into bollard luminaires, railing posts or railing terminals can be used to incorporate visual guidance and orientation aids into the walkway.

#### Installation, maintenance and power supply

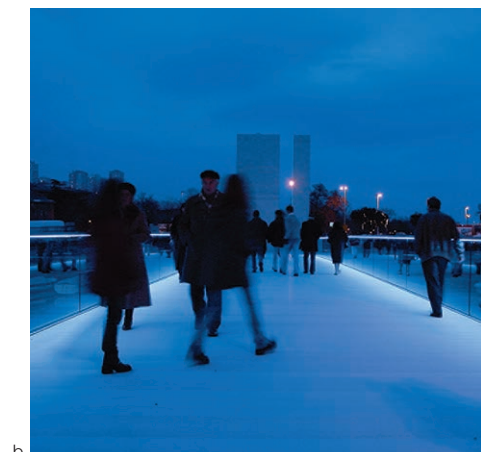
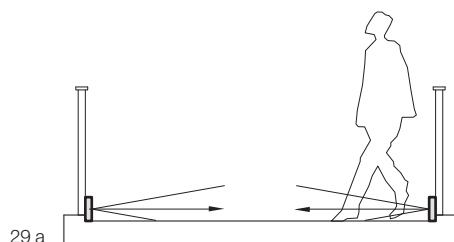
A light's position should not only satisfy functional and design criteria; its installation and maintenance must also be able to be carried out at reasonable cost and



effort. All lighting components, such as power cables, distributors, operating equipment and the connection to the power grid, should be integrated into the structure as far as possible, so that they don't seem like inept and belated additions.  
Involving an experienced, independent lighting designer at an early stage of planning and appropriate care in lighting planning will ensure that the bridge's unique and distinctive symbolic character is effectively presented, even at night.



- 24 LED lighting, integrated into the handrail, bridge memorial, Rijeka (CR) 2004, 3LHD arhitekti; C.E.S. Civil Engineering Solutions
- 25 Handrail with integrated LED lighting, Vertical section, Scale 1:5
  - a Handrail with LED lighting in a steel profile
  - b Handrail with LED lighting in a u-profile
- 26 Mast light
  - a Schematic section
  - b Pedestrian bridge Max-Eyth Lake, Stuttgart (D) 1989, schlaich bergemann and partners
- 27 Pillar light
  - a Schematic section
  - b Salinensteg Bridge, Bad Rappenau (D) 2008, schlaich bergemann and partners
- 28 Mini floodlight
  - a Schematic section
  - b Hoge Brug bridge, Maastricht (NL) 2003, Bgroup, Greisch
- 29 Light band
  - a Schematic section
  - b Bridge monument in Rijeka (CR) 2004, 3LHD arhitekti; C.E.S. Civil Engineering Solutions





## Economic aspects

Until three decades ago, purely economic considerations still governed bridge construction, however, this has changed greatly, especially for pedestrian bridge construction. The development of bridges from purely functional into symbolic, expressive structures grew out of a desire to create more than just a way of getting from A to B. Pedestrian bridges are often built in prestigious areas in cities or parks and are designed to lend their sites a unique identity, upgrading their surrounding areas and making them more attractive. A desire for something new and different demands individual ideas and solutions from architects and engineers. If they can provide these, a new bridge can make a distinctive mark and have a positive effect on areas around it. Pedestrian bridges can also be furniture or sculptures, be regarded as (art) objects, and inspire engagement with their environment as well as debate. The value of a pedestrian bridge is also far higher than the mere sum of its construction costs. It develops out of a holistic approach that includes all the positive and possibly negative influences that a bridge can have on its immediate environment. Such a costs-benefit analysis is extremely complex and must be based on many assumptions, meaning that its results are useful only to a limited extent; any conclusions reached tend to be difficult and very uncertain. For this reason, such analyses are rarely carried out and considerations are usually limited to bridge manufacturing and maintenance costs.

### Construction principles

The basic principles and tendencies outlined here are intended to contribute to the designing of appropriate and profitable bridges in the planning phase. Examples great and small show that beautiful, clear and innovative structures can be created in this way within an acceptable costs framework.

### Support system

The support system chosen and its geometry have a major influence on costs. A bridge's span should be an appropriate length and basic static principles, such as balanced overall heights in beam and truss bridges and reasonable rises in suspension, stress ribbon and arch bridges should be followed. In this context, global contingencies, such as the positioning of suspension bridge guy ropes, are just as important as local load transfer mechanisms in the bridge's cross section. Breaching these principles usually results in higher costs.

Figures available based on experience in major bridge construction demonstrate what types of bridge can be profitably built for which spans. There are also design rules that not only ensure that a bridge has appropriate dimensions and appealing proportions, but also that it fits into a specific economic framework.

Basic design principles also apply to smaller pedestrian bridges, but compared with large bridges the former offer more scope for individual design as the overall investment is usually much lower. While this potential should be used, it should not be abused because costs can otherwise increase unexpectedly and quickly, as the following example demonstrates.

A ratio of span length to rise of 1/10 to 1/12 is recommended for a back-anchored suspension bridge. If you halve the rise, the rope force is doubled, then not only is double the rope diameter required, but the foundation forces that must be anchored are also doubled. In return, the superstructure will be subject to less bending stress and the masts can be lower, but this will not offset the far greater expenses of ropes and foundations. The costs of the bridge will increase significantly. If the rise is further

reduced, costs will increase even more. Only if the structure designed is a stress ribbon bridge will it be more cost-effective, because the hangers and masts can be dispensed with and the walkway plate will be carried directly by the tension members.

It is therefore not surprising that the Millennium Bridge in London, with its extremely low rise of 1/60 was many times more expensive than a classic suspension bridge with a rise five times greater.

Planners must be aware that failure to observe tried and tested basic construction principles in a design will almost inevitably result in higher costs. In some cases the context or the impetus expected from the structure or from the design or technical innovations used to create it may justify making an exception, but the structure should not only be subordinated to purely formal demands.

It is important to critically question the classic basic principles, however, to ignore them is unjustifiable. Planners owe it to their clients and the environment to use resources responsibly and what is usually public money.

### Materials

The cost-effectiveness of various materials can be determined by simple calculations which compare their strength with the material's cost. One major parameter for the performance of a material is its maximum breaking length or threshold span limit (see Materials, p. 27). Put simply, steel and concrete have a maximum breaking length ratio of 4 : 1. If you include the material costs per m<sup>3</sup> in these considerations, which can be expressed in a ratio of about 30 : 1 (steel to concrete), and divide the maximum breaking length by that cost, you obtain a very different ratio of approximately 1 : 8. It therefore

costs around eight times more to axially transfer the same force with steel as it does with concrete.

Apart from material costs, processing costs are also significant. The raw material for steel and wooden structures must be cut to size and the pieces assembled, their surfaces may require protection from corrosion or other surface conservation measures and the pieces have to be transported and installed. Concrete structures require scaffolding and formwork, which has to be erected and taken down. Such costs can be estimated using detailed costs calculations then allocated per unit of material. These processing costs are often many times higher than the material price itself and can vary considerably. A simple, continuous steel girder with an even cross section and top flange plates welded onto it costs much less than a section that varies along its length and has to be welded together.

Such simple considerations can certainly be a guide in choosing the right material and appropriate cross sections, but they alone are not definitive design parameters because aspects such as durability, design quality or haptics may often also play a role.

#### **Span lengths**

Span length costs money. It must therefore always be carefully considered whether the selected span is really a functional necessity or whether it has been chosen for purely formal reasons. The cost of a simply supported concrete slab with a 10 to 12 m span is less than half that of a concrete slab hung on a suspended structure (span > 50 m). After determining the positions of the supports and span length, an appropriate support structure that is oriented towards the span length must be developed. As explained in the chapter on »Design and construction« (p. 32–63), different support systems are suitable for different span lengths. Economic aspects must always be taken into account here, although they should not be followed too dogmatically for pedestrian bridges, otherwise they will excessively limit the scope of the design and prevent new developments from being tested.

#### **Curved layouts**

Bridges that are curved in plan are more expensive than straight bridges. The amount of extra cost depends heavily, however, on the bridge's cross section and span length. A curving slab cast in

formwork in-situ is only slightly more expensive than a straight one, while a curved steel box girder is far more costly and complex, because it has to be assembled from individual parts whose geometry follows its curve. As little radius of curvature as possible should be used, because the many different parts it requires will result in higher costs. Curved layouts tend to play a subordinate role in bridges with shorter spans, also from a static and structural point of view, because the torsional stresses do not accumulate. In bridges with longer spans in contrast, the primary support structure also has to react to the curvature and is thereby subject to a far more complex range of stresses, which inevitably results in higher costs.

#### **Foundations and subsoil**

It is more difficult to transfer tensile forces into the ground under a bridge than it is to transfer compressive forces, because the former must be transferred either via large heavyweight foundations or by activating a body of soil connected by anchoring. The same applies for horizontal forces, which also require either a heavy-weight foundation with an appropriately high weight or a pile trestle, which can transfer forces by tension and by pressure. Large transverse bending moments can also develop on the abutments of curved bridges, which are an additional load on the foundations. These must be transferred either as shear force via friction into the foundation joint or via a pile trestle, which converts the moment into a horizontal force couple.

Long spans often require suspended structures, in which tensile and/or horizontal forces are almost inevitable. In this case, the best and most economical type of foundation should be used given the prevailing forces and site's soil conditions. Permanent anchors and micro piles, which can be manufactured with almost any pitch, have proven their worth in pedestrian bridge construction as economic types of foundation for managing tensile forces.

The soil conditions of the bridge's site will also influence its costs. Very long anchors or piles will be required for particularly deep foundations. In this case, it may be better in the interests of economy to make do with fewer foundation points and accept the need for a longer span. It is important that the site's soil conditions are understood during the design process so that they can be included in the design development.

#### **Manufacture and assembly**

A bridge's manufacture and assembly is always individual and a major element of the overall costs. Special topographical or functional requirements can make special assembly processes necessary, which will also partly determine the bridge's design and costs.

#### **Costs**

Planners are often required at a very early stage in the planning process to provide very precise information on the forecast costs. Every bridge is however a prototype and factors such as the bridge's width, site soil, topography, accessibility and installation process can majorly influence costs. It is possible at an early stage of the design to estimate the costs of a new bridge based on figures gained from experience, but only subsequent, substantiated static-structural planning and dimensioning will enable planners to make exact statements on costs.

It is always more difficult and unpredictable to try new things than to repeat old ones and it is important to make this clear to clients, especially in developing complex and new types of designs, and to persuade them that they will also have to bear part of the risk in terms of the possible costs and time required. A client will understand that the costs of a bridge with a 20 m span and a simple straight superstructure cross-section can be more quickly and precisely estimated than those for a suspension bridge with a 100 m span, a curved layout and bearings, which will require an analysis of the structure's boundary limits in its static-structural development.

#### **Cost estimates**

Once the conceptual design has been developed, an initial rough estimate of the bridge's total area can be made. This area can usually be determined by multiplying the bridge width between the railings with the total length from seam to seam. Based on built examples, figures gathered from experience are available for prices per m<sup>2</sup>, which can be calculated from the manufacturing costs of the structure for the bridge's area. Since costs can depend on many factors such as site, choice of materials, geometry, installation options and building standards etc., it requires some experience to be able to translate the existing values to new structures. The table on page 80f. shows a compilation

of the costs of a range of very different pedestrian bridges. The divergences among the same types of structures alone convey an idea of how difficult it can be to correctly estimate the costs of new bridges based on these prices.

#### Cost calculations

Once the design has been developed, a costs estimate is drawn up. The structure of this costs estimate is oriented around the structure. There are often precise specifications on this for public structures, which allow for comparisons with other structures and a consistent monitoring of costs through to the final manufacturing costs.

The costs of a structure can be calculated from the sum of the costs of individual structural elements, which arise out of the specific mass (quantity) multiplied by the exact cost (price per unit). It is important in this context that apart from a reasonable structure, details that are not yet worked out in the design are correct and taken into account across the board. In steel construction it is for example usual practice to estimate smaller parts such as stays, anchoring plates etc. with a 10 to 20% surcharge, depending on the scale of the structure. In concrete construction, the amount of reinforcing steel required is determined by means of the volume of concrete, which is multiplied by the specific reinforcement content, which ranges from 80 kg/m<sup>3</sup> for simple foundations up to 400 kg/m<sup>3</sup> for slender concrete supports, depending on the structural component.

#### Costs calculation/costing

The tender documents form the basis of the costs calculations of companies carrying out the work. These documents cover contractual regulations, technical specifications and the bill of quantities, which itemises all structural components. The documents help companies to draw up tenders and must precisely describe the construction project qualitatively and quantitatively to avoid the risk of unexpected supplementary charges and additional costs. It is therefore important, especially in the case of complex structures, to allow some scheduling and contractual leeway for the work plan – or at least a large part of it – to be developed before the tender documents are drafted. Only then will the planner be able to exactly list all items relevant to costs and protect clients from unexpected supplementary charges and additional costs.

#### Life cycle considerations

Where the planning focus was once only on construction costs, in recent years increased attention has been paid to considering costs over a structure's entire life cycle.

In the area of bridge construction, it was decided decades ago that structures should undergo structural inspections. A minor structural inspection – mainly a visual inspection – is carried out every three years. A major structural inspection, a more precise examination and survey of the structure, is made every six years. These are regulated in DIN 1076, »Civil engineering structures in the course of roads and streets – supervision and inspection«. The large number of defects identified in comparatively new road bridges during such structural inspections have made it clear that so-called Life Cycle Costs (LCC) must be included in calculations from the outset. Life cycle costs estimate the costs of a bridge over its entire service life.

These costs depend heavily on the structure in question and can vary widely, especially with bridges, and over the structure's life cycle can reach the same levels as the actual construction costs. This means that the presumed additional cost of building a robust, low-maintenance bridge must be very differently evaluated if the expected LCC are incorporated. Such a bridge, considered over its entire life cycle, can in fact be a better and more economical option.

The »Verordnung zur Berechnung von Ablösebeträgen nach dem Eisenbahnkreuzungsgesetz, dem Bundesfernstraßengesetz und dem Bundeswasserstraßengesetz (Regulation on the calculation of settlement fees in accordance with the Railways Intersection Act, the Federal Highway Act and Federal Waterways Act) also known as the Ablösungsbeträge-Berechnungsverordnung – ABBV (Settlement Amount Calculation Regulation)« issued by Germany's Federal Ministry of Transport, Building and Urban Development (BMVBS) specifies some reference values on the theoretical service life and annual maintenance costs of a bridge, depending on the type of construction and materials used. The background to the Regulation is that a party instigating a construction project must pay the related manufacturing and maintenance costs. If the German railway company Deutsche Bahn wants to build a new railway track, for example, it must reimburse the road construction authority for the

cost of restoring the existing road network and the expense of maintaining the bridge over its entire life cycle. Because this is a one-off financial settlement, maintenance of the structure must be quantified from the outset and capitalised over the structure's life cycle. The ABBV specifications apply mainly to road bridges, but can also be applied to pedestrian bridges

The construction materials used and their combined use in certain circumstances substantially determine life cycle costs. A distinction is made between reinforced and pre-stressed concrete in concrete structures. Pre-stressed concrete is not as highly rated, which is doubtless due to the many defects found in older pre-stressed concrete bridges (built in 1980 or before). Steel bridges are also ranked lower than concrete bridges, due mainly to the need to repeatedly renew their corrosion protection.

Very high maintenance costs are specified for wooden bridges (2% of construction costs annually), because they tend to show more signs of fatigue and be less resistant to weather than concrete or steel bridges. These specifications are however very generalised and do not differentiate between different kinds of wood preservation, for example. This has been criticised and rightly so, because wooden bridges with active wood protection are more impervious, resistant and durable than bridges with no such protection or those built of chemically treated wood.

Economic aspects  
Costs summary

Type <sup>1)</sup>	Bridge	Structure /Material	Length x Width [m]	Total costs <sup>2)</sup> [€]	Costs <sup>2)</sup> per m <sup>2</sup> [€/m <sup>2</sup> ]
1	Glass bridge in a research centre, Lisbon (P) 2010 	Glass tube with underslung steel structure • Superstructure: Laminated safety glass on a steel substructure consisting of longitudinal and cross girders • Surface: slip-resistant glass walking surface • Railings: Built-in glass balustrade with no extra handrail • Curved glass roofing	21 × 2.30	875,000	18,200
1	Messebrücke (Trade fair centre bridge) II, IGA Rostock (D) 2003 	Triple-span beam bridge with partial longitudinal pre-stressing • Superstructure: Reinforced concrete slab, haunched • Thin film surface on a concrete slab • Filled-rod railing (vertical)	54 × 5.50	1,076,000	3,600
1	Passerelle Simone de Beauvoir, Paris (F) 2006 	Cantilevers with suspended fish beam • Steel construction • Wooden surface with a non-slip surface • Cable mesh railing with handrail	304 × 12	23,649,000	6,500
1	Steg Cité, Baden Baden (D) 2006 	Integral concrete frame bridge with Y-shaped central supports • Superstructure: Reinforced concrete slab • Thin film surface on a concrete slab • Filled-rod railing (vertical) • Flat foundations	38 × 3	355,000	3,100
1	Bridge for Deutsche Telekom, Bonn (D) 2010 	Continuous beam on rocking piers • Superstructure: Reinforced concrete slab • Thin film surface on a concrete slab • Glass railings with stainless steel handrail • Foundations: Micro piles • Special feature: LED media band (1/3 of costs)	65 × 3	1,873,000	9,600
1	Living Bridge, Limerick (GB) 2007 	Seven-span underslung bridge • Superstructure: Steel girders • Surface: Aluminium panels • Glass railings with stainless steel handrail • Foundations: Large-diameter piles	350 × 5.50	13,249,000	6,900
2	Bridge sculpture »Slinky springs to fame«, Oberhausen (D) 2011 	Triple-span stress ribbon bridge with ramps as a continuous beam • Superstructure: Prefabricated reinforced steel components on steel plates • 40 mm coloured surface designed to protect against falls • Stainless steel cable mesh railings with handrail • Aluminium spirals • Foundations: Micro piles	406 × 2.67	5,100,000	4,700
3	Pedestrian bridge over the Hesse-ring, Bad Homburg (D) 2002 	Cable-stayed bridge • Superstructure: Reinforced concrete slab • Surface: Concrete surface with broom finish • Filled-rod railing with illuminated handrail • Pre-stressed and milled stone block masts • Foundations: Large-diameter piles	76 × 7	1,768,000	3,300
3	Pedestrian bridge over the Neckar, Esslingen-Mettingen (D) 2006 	Back-anchored suspension bridge with ramps as continuous beam • Superstructure: Reinforced concrete slab on cross girders/ paired supports • Thin film surface on a concrete slab • Filled-rod railing (vertical) • Foundations: Large-diameter piles and permanent anchor, ramp with flat foundations	295 × 3	1,914,000	2,200
3	Millennium Bridge, London (GB) 2000 	Suspension bridge with a very slight sag • Superstructure: Longitudinal steel girder hung with aluminium panels • Surface: Aluminium panels • Railings: horizontal cable with handrail • Foundations: Large-diameter piles	333 × 4	50,225,000	37,700
3	Nessebrücke, Leer (D) 2006 	Cable-stayed bridge with hinged main span • Superstructure: Longitudinal steel girder with reinforced concrete slab on cross girders • Thin film surface on a concrete slab • Filled-rod railing (vertical)	130 × 4	2,365,000	4,500

Type <sup>1)</sup>	Bridge	Structure/Material	Length x Width [m]	Total costs <sup>2)</sup> [€]	Costs per m <sup>2</sup> [€/m <sup>2</sup> ]
3	Pedestrian bridge, Innenhafen Duisburg (D) 1999	 Back-anchored suspension/lift bridge <ul style="list-style-type: none"> <li>• Superstructure: Articulated steel frame chain with pre-fabricated reinforced concrete components</li> <li>• Thin film surface on a concrete slab</li> <li>• Filled rod railing (vertical)</li> <li>• Lifting mechanism with hydraulic cylinders in the guy ropes</li> </ul>	74 × 3.50	3,234,000	12,500
4	Erzbahnschwinge bridge, Bochum (D) 2003	 S-shaped, curved, unilaterally hung suspension bridge <ul style="list-style-type: none"> <li>• Superstructure: relieved steel cross section with concrete slab</li> <li>• Thin film surface</li> <li>• Stainless steel chain link railing with no extra handrail</li> <li>• Foundations: Large-diameter piles</li> </ul>	142 × 3	2,689,000	6,300
4	Pedestrian and cyclist bridge Hafen Grimberg, Gelsenkirchen (D) 2009	 Curved, unilaterally hung, integral suspension bridge <ul style="list-style-type: none"> <li>• Superstructure: Steel box girder</li> <li>• Thin film surface on a concrete slab</li> <li>• Stainless steel cable mesh railing with no extra handrail</li> <li>• Deep foundations with piles</li> </ul>	190 × 3	42,45,000	7,400
4	Seebrücke, Sassnitz/Rügen (D) 2008	 Curved, unilaterally hung, suspension bridge with connected ramp as continuous beam <ul style="list-style-type: none"> <li>• Superstructure: Steel box girder with concrete slab</li> <li>• Ramp built in composite construction</li> <li>• Guyed tubular steel mast</li> <li>• Foundations: In-situ cast concrete piles driven into chalk cliff</li> </ul>	243 × 3	4,240,000	4,000
4	Nesciobrug, Amsterdam (NL) 2005	 Curved, unilaterally hung, self-anchored suspension bridge <ul style="list-style-type: none"> <li>• Superstructure: Steel box girder</li> <li>• Thin film surface</li> <li>• Cable mesh railing with handrail</li> <li>• Foundations: Large-diameter piles</li> </ul>	700 × 3	11,832,000	5,600
4	Passerelle La Défense, Paris (F) 2008	 Curved, self-supporting, guyed truss bridge with ring cables <ul style="list-style-type: none"> <li>• Superstructure: Steel box girder</li> <li>• Thin film surface on a steel box girder</li> <li>• Railing: horizontal stainless steel cable</li> <li>• Previously existing foundations</li> </ul>	91 × 4.50	3,789,000	9,200
5	Börstelbrücke, Löhne (D) 2000	 Twin-span stress ribbon bridge over a central arch <ul style="list-style-type: none"> <li>• Superstructure: Prefabricated reinforced concrete components on steel plates</li> <li>• Surface: Concrete</li> <li>• Stainless steel cable mesh railings with additional handrail</li> <li>• Foundations: Micro piles</li> </ul>	96 × 3.50	1,141,000	3,400
5	Three Countries Bridge, Weil am Rhein (D)/Huningue (F) 2007	 Self-anchored arch bridge <ul style="list-style-type: none"> <li>• Superstructure: orthotropic plate</li> <li>• Thin film surface</li> <li>• Railing: horizontal fill rods with handrail</li> <li>• Flat foundations</li> </ul>	248 × 5	9,937,000	8,000
5	Pedestrian Bridge, Phoenix See, Dortmund Hörde (D) 2011	 Triple-arch bridge with suspended walkway <ul style="list-style-type: none"> <li>• Superstructure: Reinforced concrete slab on cross girders, lateral arches made of bundles of rolled steel</li> <li>• Thin film surface on a concrete slab</li> <li>• Post and beam railings (horizontal) with inward sloping handrail</li> <li>• Foundations: Large-diameter piles</li> </ul>	34/38/41 × 5	1,561,000	2,800
5	Gateshead Millennium Bridge, New castle (GB) 2001	 Arch bridge with tilting mechanism <ul style="list-style-type: none"> <li>• Superstructure: Steel box girder</li> <li>• Surface: Aluminium panels</li> <li>• Horizontal filled-rod railing</li> <li>• Foundations: Large-diameter piles</li> </ul>	126 × 8	45,937,000	45,600
5	Pedestrian Bridge. Ökologischer Gehölzgarten, Oberhausen Ripshorst (D) 1997	 Spatially curved arch bridge with elevated walkway <ul style="list-style-type: none"> <li>• Superstructure: Steel box girder</li> <li>• Thin film surface on a steel box girder</li> <li>• Cable mesh railings with additional handrail</li> <li>• Foundations: Large-diameter piles</li> </ul>	130 × 3	1,750,000	4,500

<sup>1)</sup> Bridge types: 1 Beam/truss and plate bridge; 2 Stress ribbon bridge; 3 Cable-stayed/suspension bridge; 4 Curved suspension bridge; 5 Arch bridge  
<sup>2)</sup> Referenced costs for 2012 with a 2% inflation rate



## Special pedestrian bridges

Apart from fixed pedestrian bridges erected in gardens, parks and landscapes to ensure a smooth flow of pedestrians, bridges are also built to meet other, very specific demands. Examples of these include movable or covered structures or, as a special case, even platforms. Geometrical constraints combined with a lack of space may make it impossible or economically impractical to build a fixed bridge with long ramps, making a movable bridge a suitable alternative. Or particular physical demands on the structure, such as protection from wind and rain, or for air conditioning, can make the bridge an interior space. As elements of mechanical engineering and facade technology may be involved in designing such special structures, good interdisciplinary cooperation between different areas of expertise is essential. Exciting examples of such pedestrian bridges and special structures testify to the diverse range of their potentials.

### Movable bridges

Movable bridges have been built since the Middle Ages, when they were erected as drawbridges. In those days, they

served to protect castle gates or town fortifications. Today's movable bridges make it possible to travel along intersecting traffic routes without restriction. They continue to be built in place of fixed bridges if there is too little space for long access ramps and paths or if very high clearance gauges (e.g. for sailing ships) would result in extremely long ramps. The financial cost of such access is often greater than the extra cost of a movable bridge. Urban planning must also be considered, as long ramps usually require much greater intervention into existing structures. Designing movable bridges requires intensive collaboration with mechanical and structural civil engineers. While civil engineers are responsible for the structure itself, making static calculations and interpreting various states, mechanical engineers deal with issues around drive mechanism technology, interlocking mechanisms and controls.

The choice of a suitable construction type is largely determined by local conditions and the clearance gauge that must be observed. Anything that moves, espe-

cially if it is an entire bridge, attracts attention. It is not surprising then, that new and striking mechanisms are constantly being developed to highlight these movements and to make them as attractive as possible. Movable bridges are therefore a major and interesting challenge for interdisciplinary cooperation between engineers from various specialist fields.

Apart from taking fundamental principles of construction into account, it is important that as little energy as possible is expended to move a bridge. This applies to all types of structures, regardless of whether the bridge turns, swings, folds, or lifts. The movement processes described below can still be found in modern movable pedestrian bridges, although with current developments in machine technology and new, improved materials, the classic lifting and turning movements are not the only ones to be applied these days. Spectacular movement processes consisting of combinations of lifting, turning and sliding are also now being employed, as the Gateshead Millennium Bridge (Fig. 1) or the »Katzenbuckel-



1 Turn and tilt bridge, Gateshead Millennium Bridge, Newcastle (GB) 2001, Wilkinson Eyre Architects; Gifford & Partners



2

brücke« (Cat's arched back bridge) in Duisburg (Figs. 4 and 5, p. 85) impressively demonstrate.

**Drawbridges**

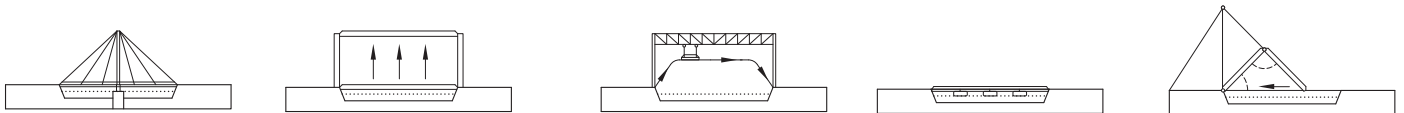
Aside from floating or pontoon bridges, the drawbridge is the oldest type of movable bridge. Using simple means such as chains, the bridge's surface was pulled up on one side in a rotary movement. Large amounts of energy were required to move these bridges, because it was not yet possible to store the energy resulting from lowering the bridge. New energy had to be generated every time

the bridge was lifted, which was then lost when it was lowered. Bascule and balanced beam bridges are different. They are also drawn by pivoting on one side, but the centre of gravity of all movable parts lies in the rotational axis, so only frictional force must be overcome to produce movement, and only very little energy is used (Figs. 2 and 7, p. 86).

**Folding bridge**

Folding is a combined process of lifting, turning and sliding. The mechanism is very complex and expensive, because there are many different intermediate

states and the movements must be exactly synchronised (Fig. 8, p. 86). Apart from the necessary space for pivots, cables and winches to move, it must be ensured that there is no danger of the primary and secondary parts of the structure colliding with each other. It is often the details for the secondary structural components such as railings that are hard to solve and frequently have a substantial influence on the design of such bridges. They make high demands on planners and require a lot of maintenance for which reasons this type of bridge is rarely built.



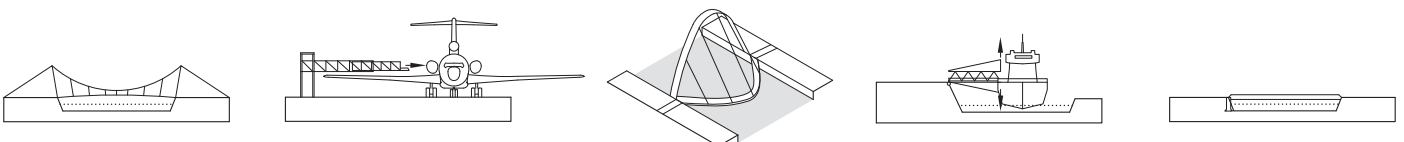
Rotating bridge

Lifting bridge

Drawbridge

Pontoon bridge

Folding bridge



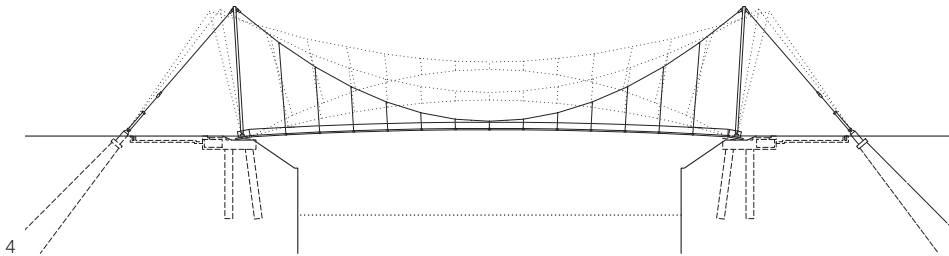
3 Swing-tilt bridge

Telescoping bridge

Suspension/vertical lift bridge

Passenger bridge

Laterally swinging bridge



**Retractable bridges**

Retractable bridges take up a lot of space, because they translate as a whole, i.e. without turning. Their guides and foundations are very complex as the support points shift and the bridge requires abutments that can transfer loads through every intermediate state into the ground.

The advantage of these bridges is that their centre of gravity shifts horizontally meaning that only frictional energy must be used in the process and no additional weights are necessary for energy storage. Special demands are

made on the support structure if the static system completely changes during movement due to the absence of one abutment.

A bridge girder moved along its centre line must then function not only as single-span girder, but also as a cantilever beam, although only under its own weight.

**Swing bridges**

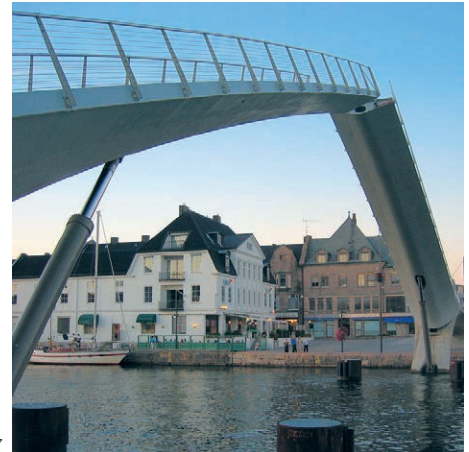
Swing bridges are like retractable bridges, although with the advantage that their support point does not shift, but remains stationary (Fig. 6, p. 86). Movements



- 2 Drawbridge, Tervaete (B) 2004, Ney + Partners
- 3 Selection of movable bridge types
- 4 Back-anchored suspension-vertical lift bridges, View showing the three possible lifting positions, pedestrian bridge, Innenhafen Duisburg (D) 1999, schlaich bergemann and partners
- 5 Pedestrian bridge in the Duisburg Innenhafen in the raised position



6



7

can therefore be made using simple and compact drive mechanisms, as long as the structure's centre of gravity remains in the pivotal point. If this is the case, only mainly vertical reaction forces develop and the abutment can be a simple one.

While a retractable bridge sweeps over a rectangle or parallelogram, a rotational movement describes a segment of a circle. Both movements require a great deal of space.

#### Rolling bridges

The upper chord of a rolling bridge is continuously shortened by a scissor mechanism, which rolls up the bridge in a very spectacular manner. This mechanism is an example of how a whole bridge can be moved using vertical hydraulic cylinders with many small forces (Figs. 9 and 10).

#### Telescoping bridges

Telescoping bridges are used mainly as access aids for aircraft. Telescoping individual bridge elements alters the bridge's length and with additional mechanisms, these bridges can be moved up and down and turned. This allows for quick and individual adjusting to various access

situations, which are determined by the aircraft's position and size. Telescoping bridges should perhaps be assigned to the area of mechanical engineering, because their technology is based more on their movement mechanisms than on their support structures. They are also less subject to aesthetic requirements and are primarily functional.

#### Materials

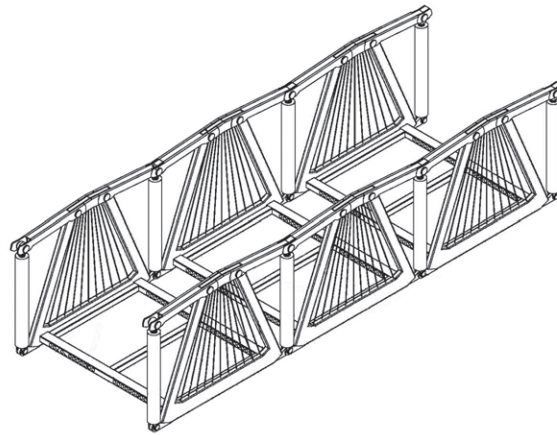
Movable bridges should preferably be light so that as little mass as possible has to be moved, meaning that materials such as steel and aluminium, but also wood and fibre-reinforced plastics are suitable. The carbon-fibre reinforced plastic bascule bridge in Fredrikstad demonstrates, for example, the potentials that such new materials offer (Fig. 7). The bridge has a 56 m span and both halves of it can be folded up without a counterweight, each using just one hydraulic cylinder. It weighs a total of 40 t.

Concrete is very suitable for counterweights and has a far more favourable ratio of weight to cost than steel. The fact that concrete takes up to three times as much space as steel does at the same weight can however be a disadvantage.



8

- 6 Swing bridge over the Alter Hafen (old harbour), Bremerhaven (D) 2007, nps tschoban voss; WTM Engineers
- 7 Carbon-fibre reinforced plastic bascule bridge, Fredrikstad (N) 2006, Griff Arkitektur; FiReCo
- 8 Folding bridge, Kiel-Hörn (D) 1997, gmp Architekten von Gerkan, Marg and Partners; schlaich, bergemann and partners
- 9 Construction scheme, Rolling Bridge, London (GB) 2004, Heatherwick Studio; SKM Anthony Hunts
- 10 Rolling movement of the Rolling Bridge



9

#### Drive mechanisms

Hydraulic aggregates or electric motors are mainly used to operate movable bridges. Hydraulic drive mechanisms work with oil pressure cylinders. They can produce great force and make very little or no noise. The pressure can be distributed through pipelines, so the engine room and cylinders do not have to be close to the structure. Hydraulic cylinders must be redundant and should not take on any permanent static force to avoid endangering the structure's stability if there are any leaks or if hose-pipes burst.

Electric motors, like petrol or diesel motors mainly perform rotational movements. Their rotation speeds are so high however, that they can only be used with appropriate translations in the form of gears and winding tackle for movable bridges. Mechanisms such as gear racks and cable winches translate the rotational movement into shifting motion. By choosing the translation, it is possible to control its force and course. A motor can use the same power to move a bridge either a short distance with great force or a longer distance with less force. The length of cylinders in hydraulic aggregates limits the lengths that can be travelled, although very long cables wound onto winches make it possible to cover much longer distances, even if they are coiled onto winding tackle.

Cable winches impose very high alternating stresses on cables, because they are constantly bent when they run over the sheaves. They are therefore fundamentally different from standing ropes in their composition and fatigue resistance and are subject to much higher safety requirements.

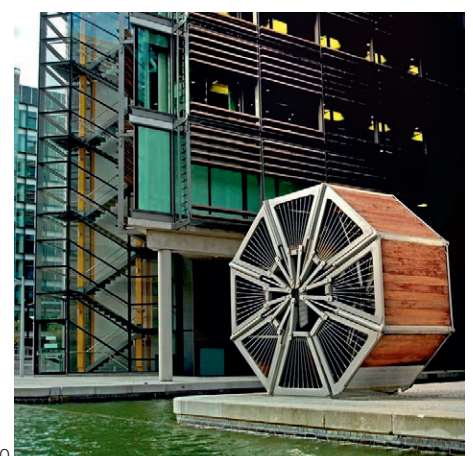
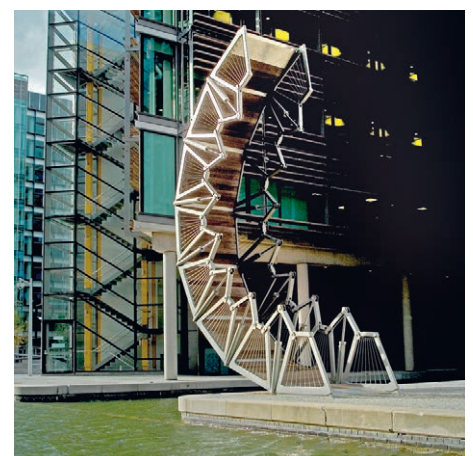
#### Covered bridges

The first roofed bridges were built less to protect pedestrians than to protect

the bridge. Lucerne's medieval Chapel Bridge, for example, is almost entirely encased. A projecting roof protects its wooden support structure from the direct impact of the weather. Newer wooden bridges also use this protective principle for wooden support structures, where it is implemented with contemporary joining technologies (Figs. 11–13, p. 88). Bridges that connect buildings, in contrast, are designed to protect people passing over them from the weather, on their way into the adjacent building. A single-layer waterproof and windproof shell is enough for protection from wind and rain alone. If air conditioning is needed, additional measures on the roof and facade will be required to provide climate protection of the kind used in buildings (Figs. 14 and 15, p. 88).

All types of hollow cross sections (circular, square, elliptical or polygonal) can be used for such connecting bridges. Rectangular or square cross sections are normally used however, because their flat surfaces are easier and less expensive to clad than curved ones.

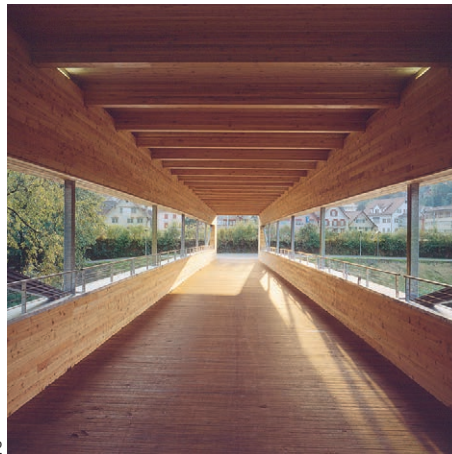
Facade elements made of glass, metal, plastic and wood can be used for rigid cladding. Free forms, in contrast, can be covered with translucent, individually fitted textile covers. An air-conditioned interior space can only be provided in this context with a double-layered shell, which does however have a negative impact on the structure's translucency. The interiors of glazed structures can become very hot such that, as with buildings, appropriate protection from the sun must be provided, either in the form of heat insulating glazing or by external shading elements. Adequate ventilation of the interior space must also be ensured. This can be achieved through natural airflow or skilfully arranged ventilation holes or slits.



10



11



12



13

Because of the clearance gauge that must be kept unobstructed to allow free passage, covered bridges have a structural depth that can be efficiently used in the support structure, with the floor used as the lower chord, the roof as the upper chord, and shear connectors in the form of frames or diagonals integrated into the facade. The disadvantage of this is that these elements are visible and detract from the users' view of the outside, or at least influence it. For this reason, the bridge elements, ropes or rods, should be as transparent as possible with minimal cross sections.

Very long spans can be achieved with a 3 metre-high closed tube, which takes on both static and functional roles. Intermediate supports are however still built in many cases, because the capacity of the support points in existing buildings is often limited. Complex and expensive reinforcement and strengthening measures are often necessary in old buildings in particular. It may then be better to choose a stand-alone, inherently stable structure, which transfers no or only very slight forces into the existing structure.

When the support structure has been selected, the positioning of any supports

determines how it is integrated into the façade. The options range from truss and Vierendeel structures to suspended structures. As the latter only require one chord, their suspension points can be installed above roof level (Fig. 15). Because closed tubes are subjected to much higher wind loads, adequate lateral stability of the tube itself and its support points must also be ensured. Frames are a suitable way of laterally stabilising a tube and can at the same time be used as truss rods for longitudinal support. If buildings cannot absorb horizontal forces, separate supports adequately anchored in the ground must take on this function.

### Platforms

Some bridges lead straight to a place that cannot be reached under normal conditions rather than over or past something; very special views can be had from them. A trend of attracting tourists with spectacular observation platforms is growing (Fig. 16–19), particularly in developed mountainous areas. Such structures require a high level of design sensitivity. They must respect their natural surroundings and be integrated into them, so that they are not 'alien elements' in the landscape.

Platforms often have a large cantilever, so they are exposed to static as well as dynamic loads. Their vibration behaviour must therefore be precisely investigated to avoid causing queasiness or even fear among visitors due to unpleasant movements or speeds. This can be achieved by installing dynamic vibration absorbers.

Platforms must be securely anchored to the ground without being subjected to subsidence or lifting. Ground conditions play a major role here. Solutions for rocky and uneven ground are often required, especially in mountainous regions. Permafrost soils, which occur in some high mountain regions and in the Alps, represent a particular challenge. It is especially difficult to permanently and securely anchor support structures in such places. There is also a risk that the frozen ground will thaw over the long term, changing its mechanical properties entirely. Long piles or anchors in non-frozen zones must often therefore provide anchoring for such structures.

Another vital aspect that can influence design and construction is the issue of actually building such platforms. The inaccessibility of many areas often makes it impossible to directly manufacture parts



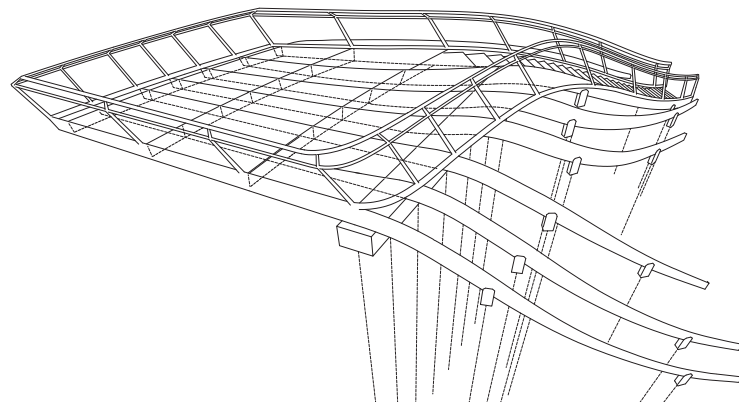
14



15



16



17

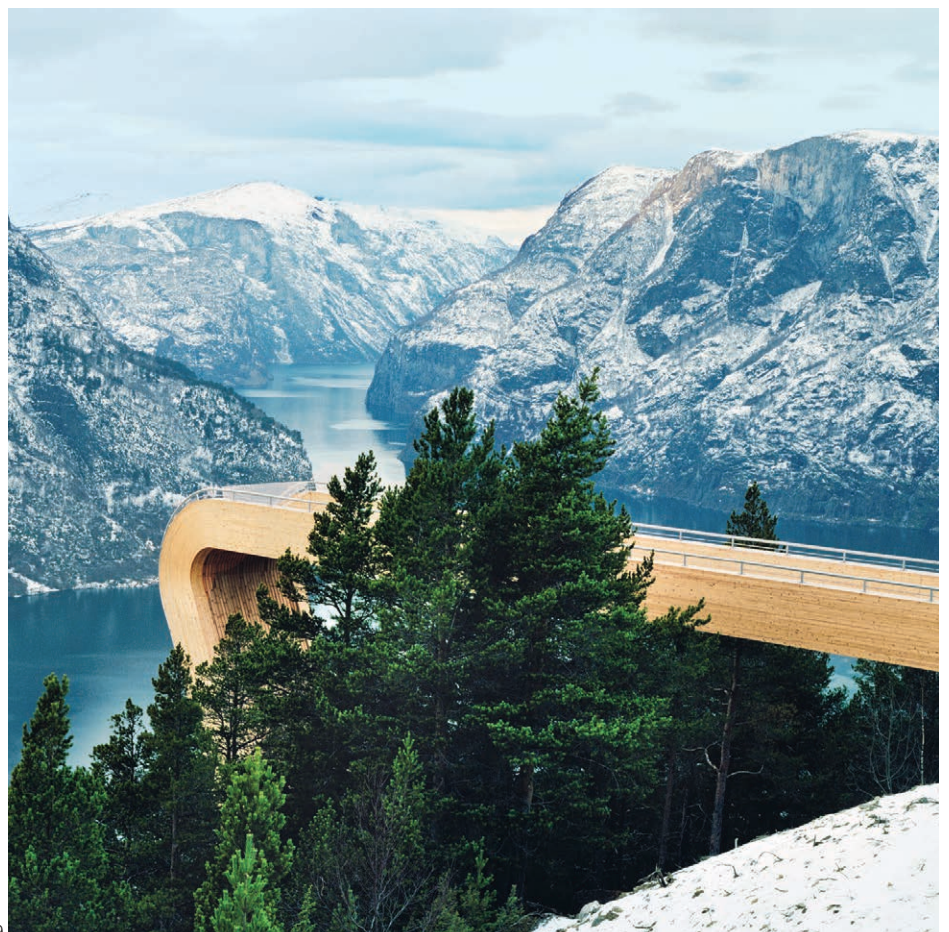
on site, meaning that all structural components should be delivered to site as prefabricated as possible for ease of installation. Installation by helicopter may also be necessary. This requires great skill and extreme precision on the part of both the helicopter pilots and the planners. All parts must be carefully weighed and their installation precisely planned, as subsequent adjustments or corrections can cost a great deal of time and money in such difficult conditions.



18

- 11 Zinkenbach Bridge, St. Gilgen am Wolfgangsee (A) 2008, Halm Kaschnig Architects; Kurt Pock
- 12 Roofed wooden bridge, Gaissau (A) 1999, Hermann Kaufmann; Franz Dickbauer
- 13 Pedestrian bridge, Boudry (CH) 2003, Geninasca Delefortrie; Chablais Poffet
- 14 Skywalk Rennweg, Vienna (A) 2009, SOLID architecture; RWT Plus
- 15 Pedestrian bridge, Bietigheim (D) 1994, Noller Architects; schlaich bergemann and partners
- 16 Observation platform »AlpspiX«, near Garmisch-Partenkirchen (D) 2010, Wallmann Architects; Acht Ziviltechniker
- 17 Axonometry, »Top of Tyrol« mountain platform, Stubai Glacier (A) 2009, LAAC; Aste Weisteiner
- 18 »Top of Tyrol« mountain platform, Stubai Glacier (A)
- 19 Lookout bridge, Aurland (N) 2006, Todd Saunders, Tommie Wilhelmsen

19



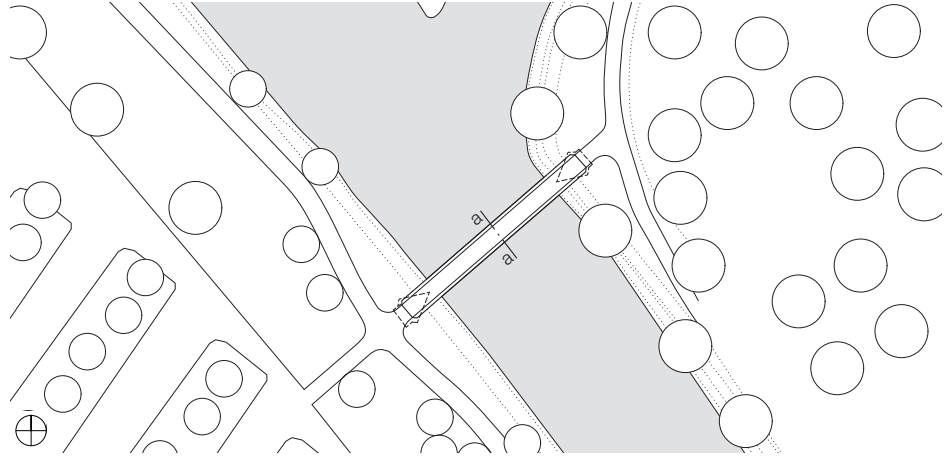


## Built pedestrian bridges

- 92 Pedestrian and cyclist bridge in Eichstätt (D)  
Christian Vogel Architekten, Munich  
Grad Ingenieurplanungen, Ingolstadt
- 94 Alfenz Bridge in Lorüns (A)  
Marte.Marte Architekten, Weiler  
M+G Ingenieure, Feldkirch
- 96 Sackler Crossing, Kew Gardens, London (GB)  
John Pawson, London  
Buro Happold, London
- 98 Bridge over the Gessental Valley near Ronneburg (D)  
Richard J. Dietrich, Traunstein  
Köppl Ingenieure, Rosenheim
- 100 »Slinky springs to fame« bridge sculpture in Oberhausen (D)  
schlaich bergemann and partners, Stuttgart  
Tobias Rehberger, Frankfurt a. M.
- 102 Bridge on the Trift Glacier (CH)  
Ingenieurbüro Hans Pfaffen, Chur
- 104 Pedestrian and cyclist bridge in Knokke-Heist (B)  
Ney & Partners, Brussels
- 106 Media City Footbridge in Salford (GB)  
Wilkinson Eyre Architects, London  
Ramboll UK, Southampton
- 108 Pedestrian and cycle path bridge,  
Hafen Gimberg (Port Grimberg), Gelsenkirchen (D)  
schlaich bergemann and partners, Stuttgart

## Pedestrian and cyclist bridge in Eichstätt (D)

Architects: Christian Vogel Architekten,  
Munich  
Contributor: Rafael Schullik  
Structural designer: Grad Ingenieurplanungen,  
Ingolstadt  
Completed: 2009



This delicate bridge for pedestrians and cyclists, which crosses the Altmühl River in the Bavarian town of Eichstätt since 2009, is distinguished by its restrained elegance. Without additional supports the bridge's elegantly flat arch spans the river and with its low constructional depth it appears to almost float.

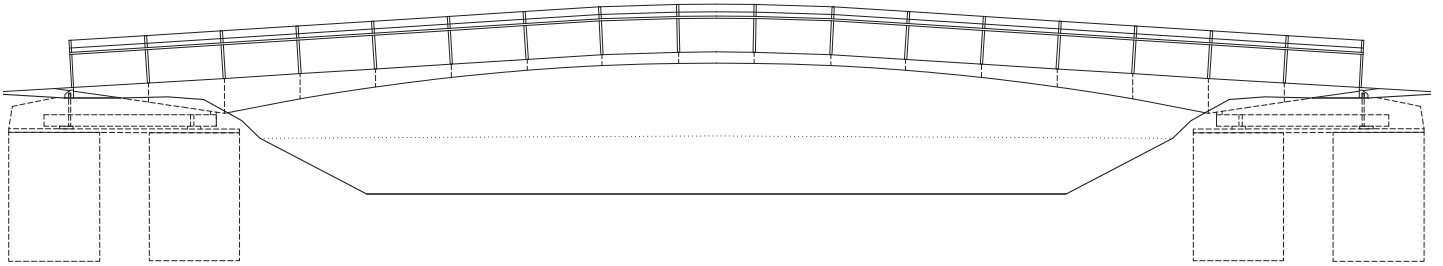
There were a number of major challenges involved in designing this bridge. The structure had to ensure free passage for boats and withstand a German category HHW 100 flood.

The planners designed a smooth, fish belly-shaped cross section with a total

length of approximately 35 m and a maximum width of 3.50 m. Despite its long span, the steel box girder's structural depth, at just 30 cm in the middle of its span and 90 cm at its abutments, is very low. On the one hand, this reduction to the necessary minimum enables the bridge to achieve its filigree appearance. On the other hand, its low static height, which still complies with the prescribed flow height clearance, means that the bridge's ends land at around the height of the existing path, so only slight adjustments to the banks were necessary.

The structure is supported by a torsionally stiff steel beam fixed at both ends with 7 longitudinal and 18 transverse ribs set in a 2 m grid. Any horizontal and torsional forces resulting from unilateral loads or forces from floods carrying flotsam are transferred via triangular concrete foundations into two ring foundations.

The railing, which can be disassembled in the event of flooding, has also been reduced to a minimum of materials and underscores the structure's lightness. Its surface is slip-resistant asphalt.

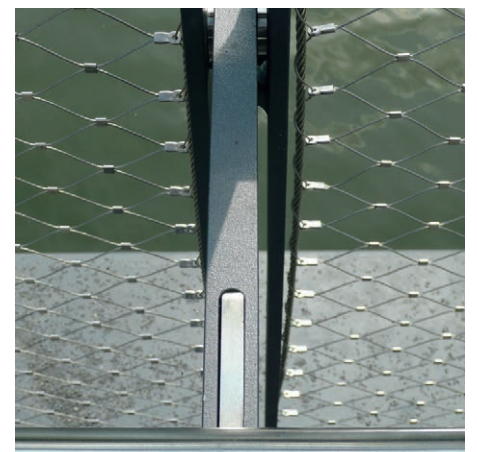
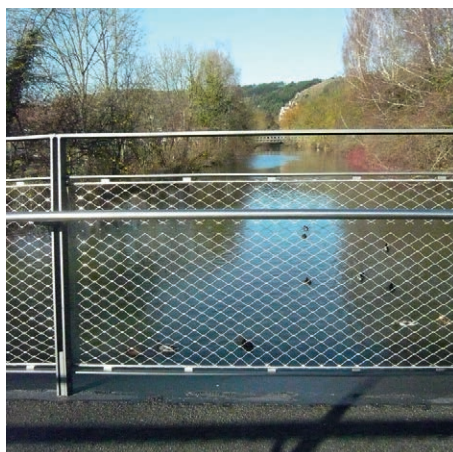
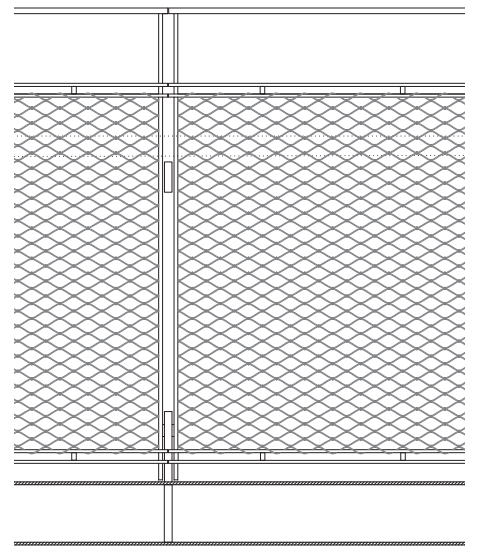
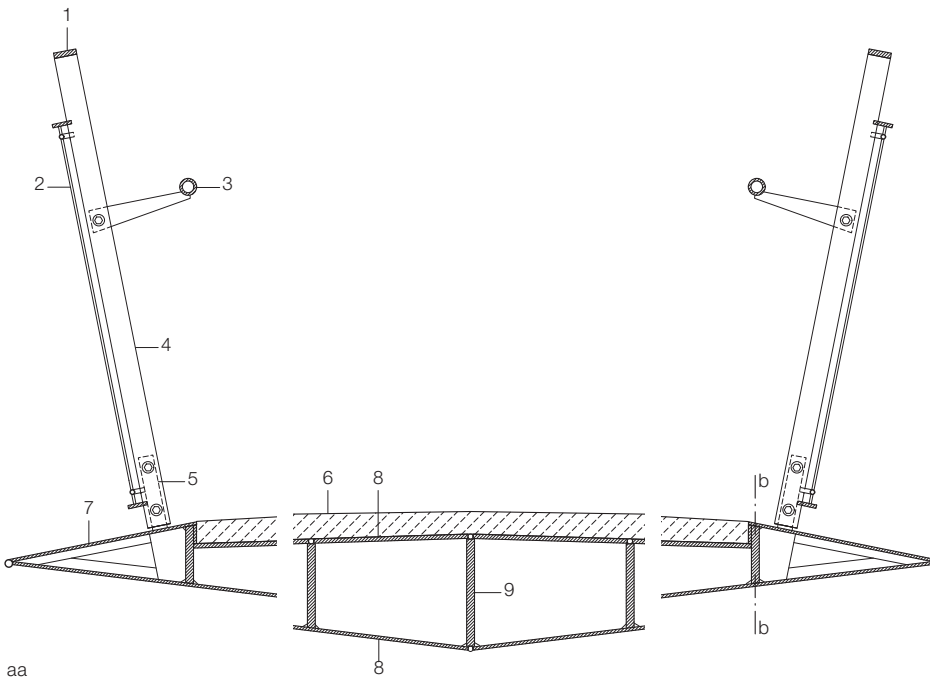


Site plan Scale 1:1000  
Side view Scale 1:200  
Vertical section Scale 1:20

- 1 Flat steel, hot-dip galvanised  $\square$  20/40/210 mm
- 2 Railings, stainless steel mesh  $\varnothing$  1.5 mm  
Mesh size, 50 mm, spanned on flat steel
- 3 Handrail, steel tube  $\varnothing$  42.4/3.2 mm
- 4 Handrail supports, flat steel  $2 \times \square$  60/10 mm

- 5 Web, flat steel, hot-dip galvanised  $\square$  20/40/210 mm, connected to the railing supports by countersunk bolts
- 6 Walkway surface: Slip-resistant asphalt, 60 mm
- 7 Steel plate 5 mm
- 8 Box girder, steel plate 10 mm
- 9 Longitudinal ribs, steel plate 20 mm welded to transverse ribs with a three-sheet weld seam

Structure:	Arch bridge
Material:	Steel
Total length:	34 m
Span length:	26 m
Width:	max. 3.5 m
Surface area:	130 m <sup>2</sup>
Superstructure height:	30–90 cm



## Alfenz Bridge in Lorüns (A)

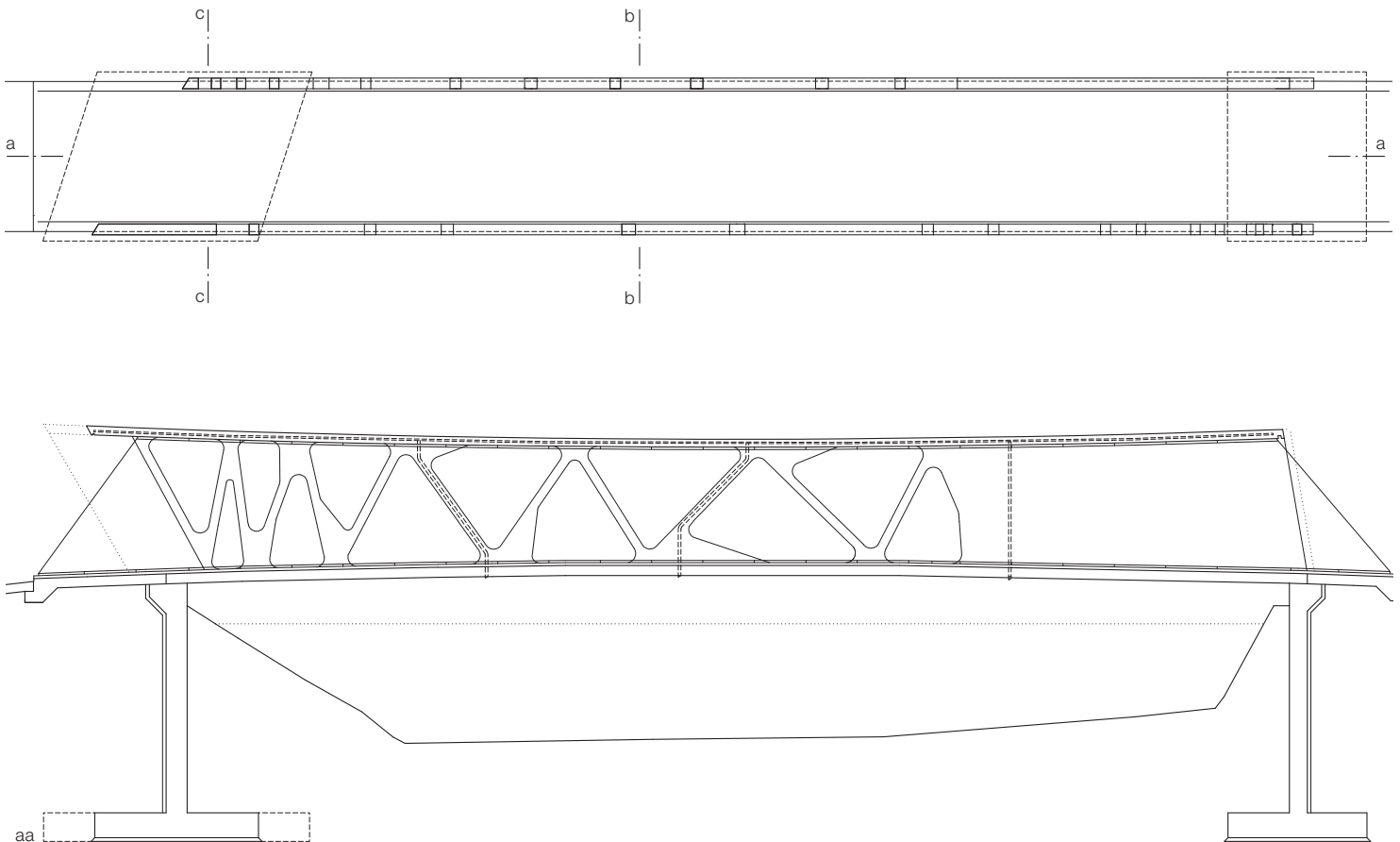
Architects: Marte.Marte Architekten, Weiler  
 Contributors: Bernhard Marte, Clemens Metzler  
 Structural designer: M+G Ingenieure, Feldkirch  
 Team: Josef Galehr, Rolf Ennulat, Clemens Beiter  
 Completed: 2010



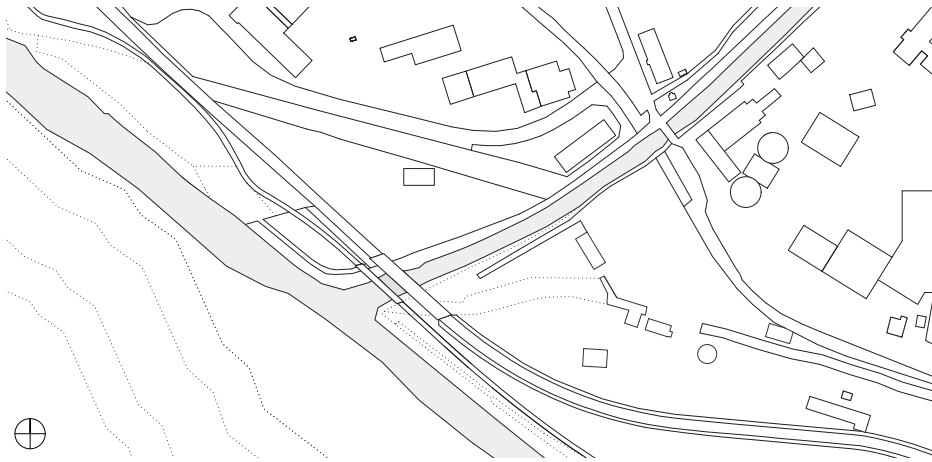
An unusual bridge has been built not far from the small town of Lorüns in Austria's Vorarlberg region; it looks more like a sculpture than a civil engineering structure. The Alfenz Bridge marks the entry to the Montafon Valley, through which the Ill River flows, a rushing river that often causes major flooding. Situated a few metres from where the Alfenz flows into the Ill, the new concrete bridge over the river provides walkers and cyclists with a secure crossing point. Its planners faced some major challenges. High-voltage power lines in the vicinity

meant that only a small area was available as a building site. An underlying support structure could not be built because of the way it is connected to the riverbank and flood protection requirements. A wooden structure was impossible because of the risk of a possible spark discharge. The planners therefore proposed a covered concrete bridge supported by its side walls whose box form re-interprets the classic truss bridge. The structure consists of 4.30 m high fair-faced concrete trusses along the sides that are joined to the deck and floor slab and function as

the bridge's upper and lower chords. Modelled on bionic principles, irregularly positioned tension and compression rods with reinforced ends form an open bridge structure. The angles of the truss frame braces follow the course of transverse force, becoming steeper towards the supports. A massive wall screens the bridge from the busy road to the north. To the south, the irregular truss opens up views into the surrounding natural area. The bridge therefore reacts naturally to static influences while at the same time integrating into its environment.



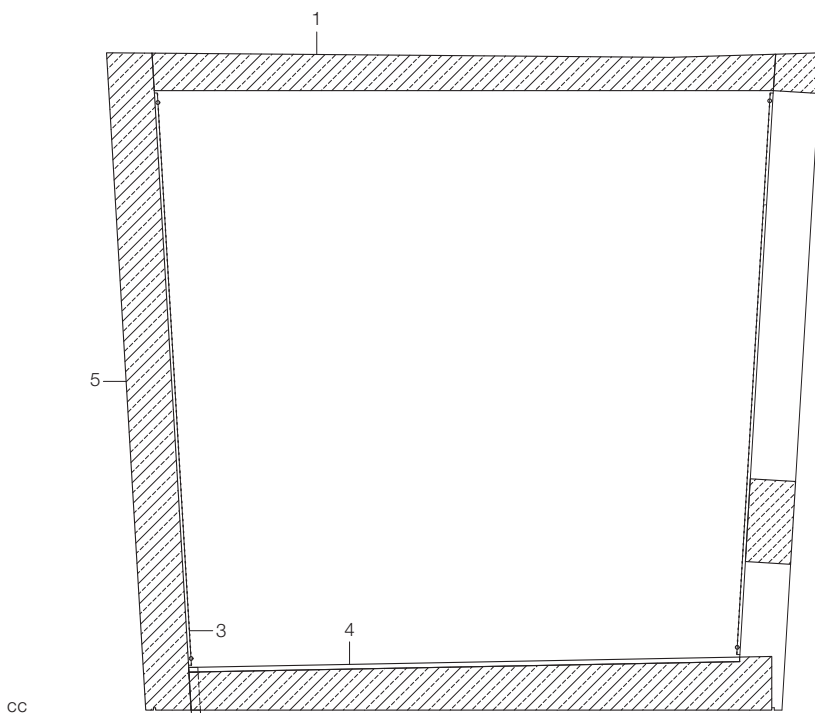
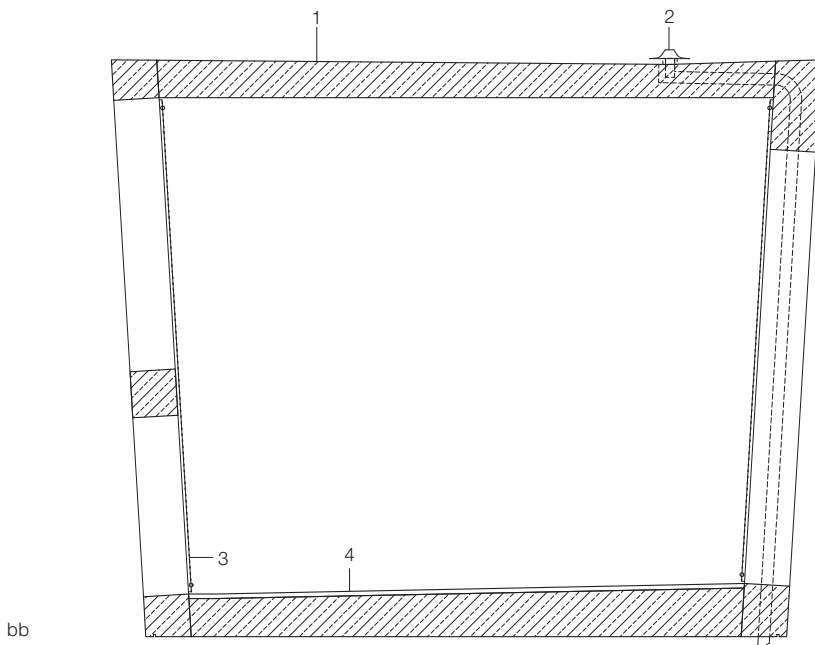
Examples of structures  
Alfenz Bridge in Lorüns (A)



Top view • section Scale 1:200  
Site plan Scale 1:5000  
Vertical section Scale 1:50

- 1 Deck, fair-faced concrete, untreated 250 mm, sloping
- 2 Roof drainage, deck element, stainless steel
- 3 Railings, stainless steel mesh  $\varnothing$  1.5 mm  
Mesh size, 80 mm spanned on a stainless steel cable  $\varnothing$  8 mm
- 4 Floor structure:  
Surface, hard concrete with broom finish 2 mm  
Fair-faced concrete, untreated 250 mm, sloping
- 5 Fair-faced concrete, untreated 300 mm

Structure: Truss bridge  
Material: Concrete  
Total length: 38.30 m  
Span length: ca. 33 m  
Width: 4.20–4.70 m  
Bridge surface area: 116 m<sup>2</sup>  
Superstructure height: 3.80–4.30 m



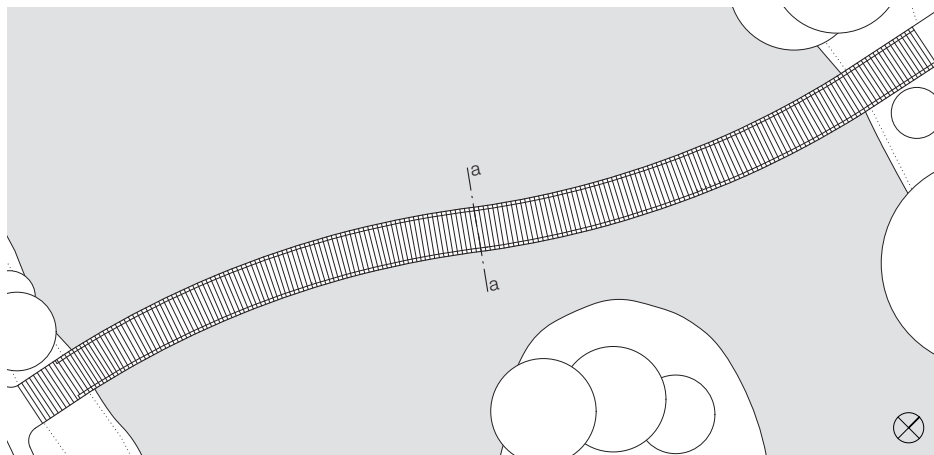
## Sackler Crossing in Kew Gardens, London (GB)

Architect: John Pawson, London  
Team: Ben Collins, Chris Masson, Vishwa Kaushal  
Structural designer: Buro Happold, London  
Team: Simon Fryer, Chris Woodfield, Anthony Holder  
Completed: 2006

The Royal Botanic Gardens are in Kew, south-west of London and are home to the world's largest collection of different plant species. The botanical garden complex, which was declared a Unesco World Heritage Site in 2003, is one of the oldest of its kind. It was developed almost 250 years ago from several smaller gardens, which were all in the possession of the royal family. In subsequent years they grew together to form a large park, which was planned by various landscape architects. The park's buildings, including the renowned Victorian greenhouses, have now been complemented by another structure: the Sackler Crossing – named after Mortimer and Theresa Sackler, whose foundation financed its construction.

It spans the larger of two artificial lakes in the western part of the grounds. In the overview the bridge forms a sine curve, meanders between two densely vegetated islands and thanks to its double curve offers various views of its surroundings from different angles.

Seen from far away, it is barely perceptible, because the slender extruded bronze railing posts, with a diameter of 2.5 cm, provide transparency and the interplay of their colouring means that they fit in perfectly with their immediate environment. Standing on the banks of the lake, the curving bridge's parapet looks like a solid wall because of the optical overlapping of the bronze rods. The reflections of the shimmering railing posts in the rippling water are delightful. Because the bridge sits very low over the water's surface, visitors crossing it gain an impression of the close proximity of the water, which shimmers through the joints between the dark granite joists. Small LEDs have been integrated into these, which illuminate the bridge and the water when it is dark.



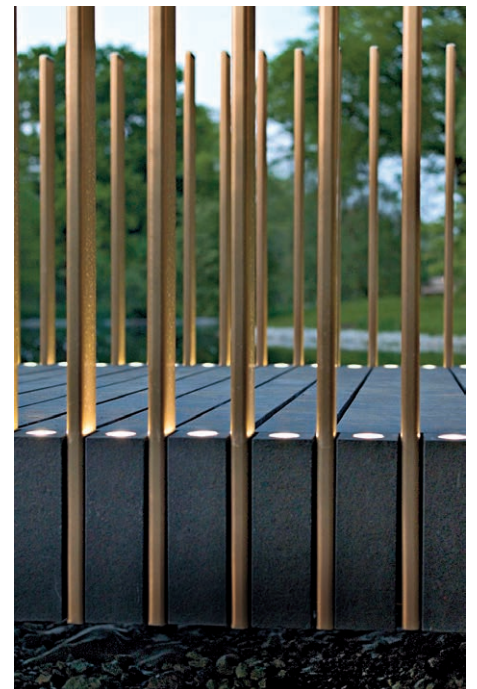
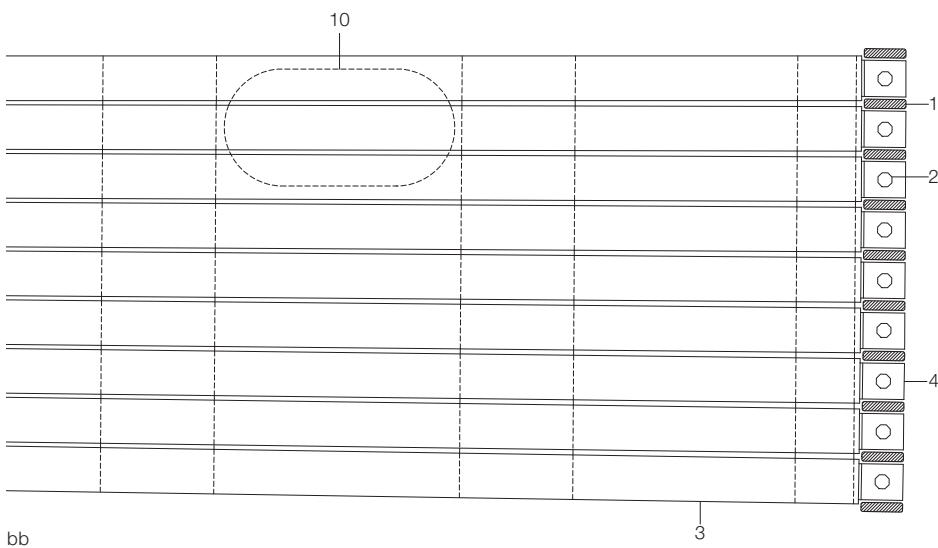
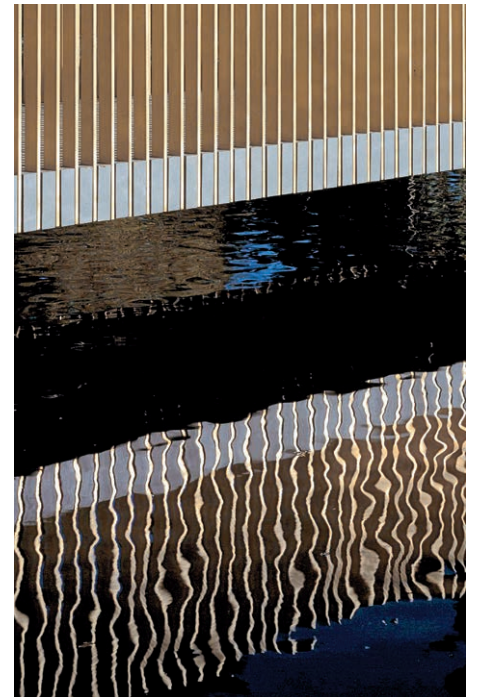
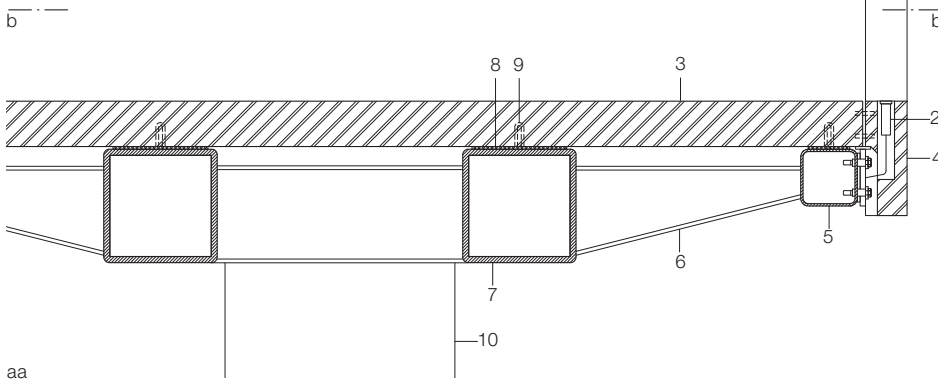


Structure: Beam bridge  
Material: Steel  
Total length: 102 m  
Span length: 28 m/46 m/28 m  
Width: 3 m  
Bridge surface area: 306 m<sup>2</sup>  
Superstructure height: 28–44 cm

Site plan  
Scale 1:500  
Vertical section • Horizontal section  
Scale 1:20

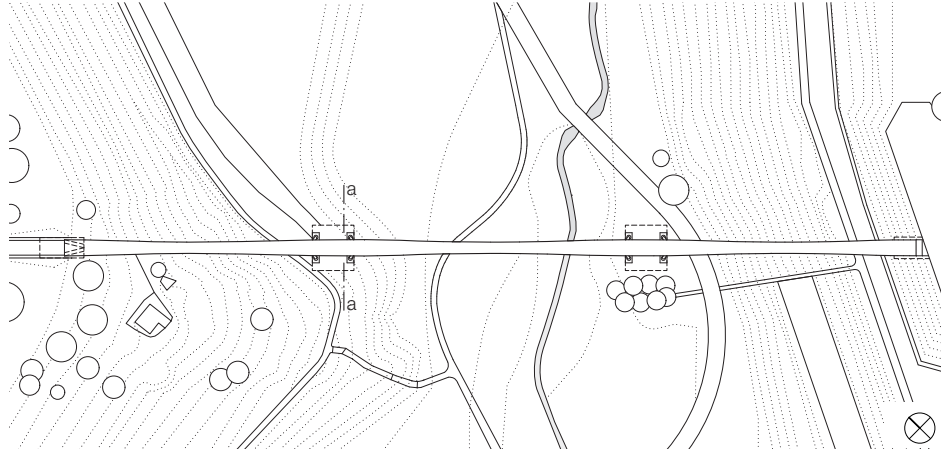
- 1 Posts, bronze 110/24 mm with welded on attaching plates, 16 mm
- 2 LED floor lights 1 W
- 3 Granite joist 120/99–104 mm, joint 10–15 mm, drill holes Ø 12 mm, t = 60 mm, filled with epoxy resin and

- pressed in with steel pins
- 4 Moulded part, granite 80/300 mm
- 5 Stainless steel tubing  $\varnothing$  150/150/6,3 mm
- 6 Bracing, stainless steel, welded, flat steel  $\varnothing$  10 mm
- 7 Stainless steel tubing  $\varnothing$  300/300/16 mm
- 8 Bearing, neoprene strips 250/ 5 mm
- 9 Steel pin, stainless steel  $\varnothing$  10 mm, welded to stainless steel tubing
- 10 Piers, stainless steel



**Bridge over the Gessen Valley near Ronneburg (D)**

Object and structural design: Richard J. Dietrich, Traunstein  
 Contributor: David Oppermann  
 Statics and dynamics: Köppl Ingenieure, Rosenheim  
 Contributor: Johann Bleiziffer  
 Completed: 2006



Extremely light and elegant, this wooden stress ribbon bridge rises 25 metres above the Gessen Valley in the 'New Landscape Ronneburg', which was developed on a former uranium mine site as part of Germany's Federal Garden Show in 2007. The bridge is part of the Towns of Thuringia Long Distance Cycle Route (Fernradweg Thüringer Städteketten) and with a total length of 225 metres is one of the world's longest wooden bridges. At its highest lookout point, the bridge widens and offers an unimpeded view across the recultivated landscape.

The stress ribbon structure, made of block-glued laminated timber, stretches like a taut rope from pier to pier. Its profile, just 50 centimetres deep, is divided into three self-supporting spans, 52.50 metres, 55 metres and 52.50 metres long. This extremely slender cross section is made possible by the almost exclusive transfer of loads by tensile force. Tensile forces of approximately 800 tonnes are absorbed by massive concrete abutments, which are clamped to 14 ground anchors in the stony ground. 25 metre high, tree-like tubular steel support pillars hold the slightly curved ribbon.

The stress ribbon has a sag of approximately 2.30 metres in each span. To prevent the walkway from sloping too steeply, additional glued laminated timber beams are doubled up on the stress ribbon, which increase in height towards the middle of the spans and reduce the slopes. These are simply screwed on and can therefore also damp vertical vibrations through friction. Horizontal torsional vibrations are checked by the ribbon's slender "waist".

This very economical structure, including the steel coupling elements and 25 to 30 metre long parts of the railings, was prefabricated in a plant and then installed on site.



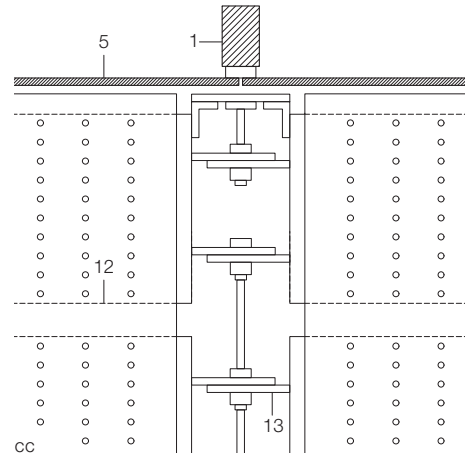


Site plan Scale 1:2000  
 Vertical section • Horizontal section, Coupling  
 Stress ribbon Scale 1:20

- 1 Railing posts larch wood 160/100 mm  
Coping, steel sheeting, 2 mm
- 2 Handrail, larch wood profile  $\varnothing$  80 mm
- 3 Railing infill, steel wire net 40/40/4 mm on a tubular steel frame, hot-dip galvanised  $\varnothing$  26.9/3.2 mm
- 4 Railing attachment with screws M 16
- 5 Weather-proof cladding, plywood 16 mm

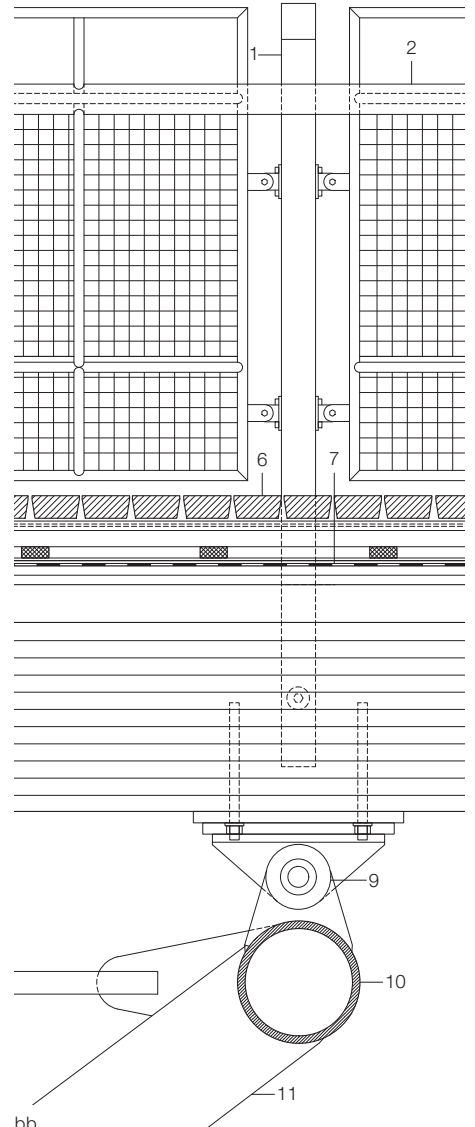
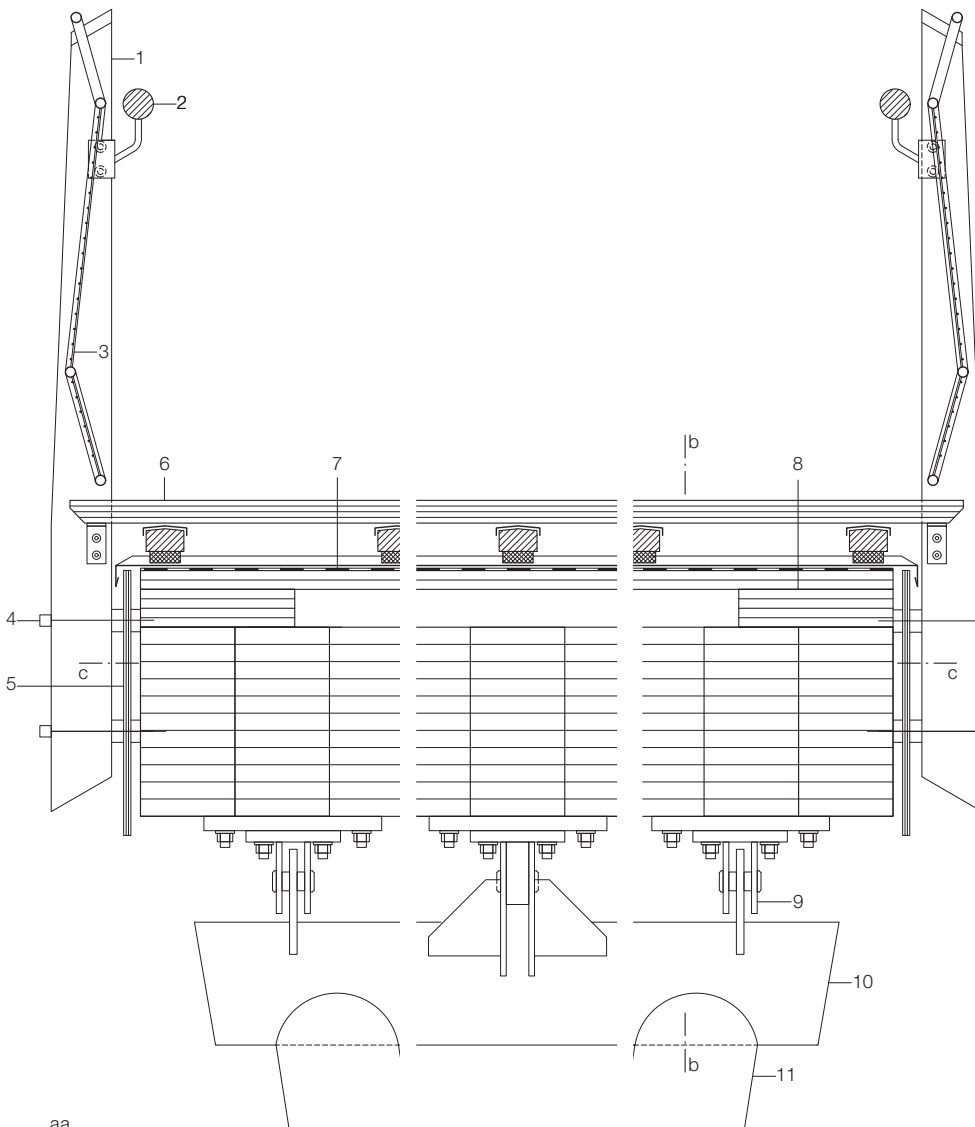


- 6 Surface, larch planks 60/140 mm  
Squared timber 30/40 mm, covered with neoprene band on spacers, synthetic Sealing, aluminium sheeting 0.7 mm
- 7 Veneer laminated timber slab 51 mm  
Underlay, fibreglass reinforced plastic
- 8 Doubling-up, glued laminated timber 100–500 mm, screwed onto the stress ribbon,  
Glued laminated timber block-glued 500 mm
- 9 Pivoting bearing element that moves longitudinally and laterally
- 10 Side profile, steel tubing  $\varnothing$  323.9/20 mm



- 11 Struts, steel tubing  $\varnothing$  457/20 mm
- 12 Slotted plates with steel dowels  $\varnothing$  16 mm, 3 rows of 8 pieces each
- 13 Coupling stress ribbon

Structure: Stress ribbon bridge  
 Material: Wood  
 Total length: 225 m  
 Span length: 52.50/55.00/52.50 m  
 Width: 2.50–4.00 m  
 Bridge surface area: 715 m<sup>2</sup>  
 Superstructure height: 10–50 cm

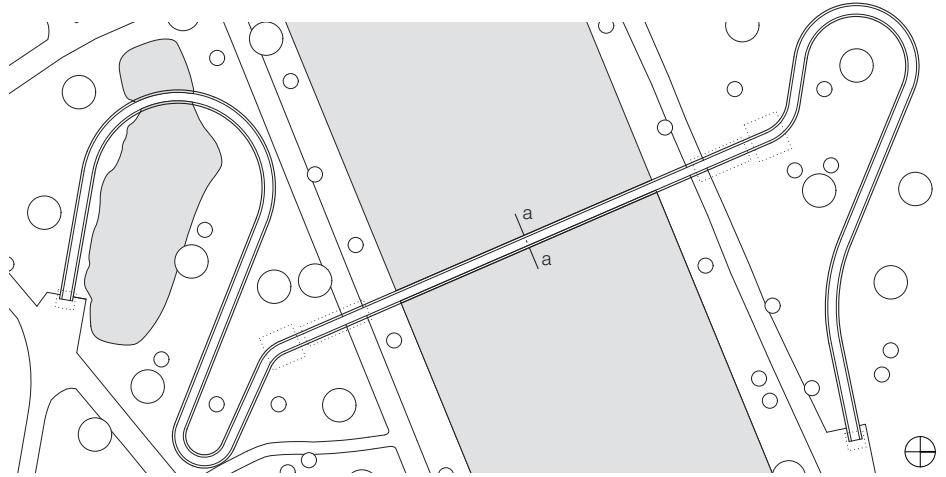


aa

bb

**»Slinky springs to fame« bridge sculpture, Oberhausen (D)**

Structural designer: schlaich bergemann and partners, Stuttgart  
Team: Mike Schlaich, Mathias Nier, Arndt Goldack, Sarah Peters, Christiane Sander, Ulrich Schütz, Rüdiger Weitzmann  
Artist: Tobias Rehberger, Frankfurt a.M.  
Completed: 2011



This sculptural pedestrian bridge over the Rhine-Herne Canal in Oberhausen created a new connection between the Kaisergarten and Emscher Island Parks. The planners developed the concept in collaboration with artist Tobias Rehberger as part of the »EMSCHERKUNST.2010« project. With an S-shaped ramp on one side and a U-shaped ramp on the other, the bridge's coloured band, encased by 496 hollow aluminium coils, straddles the canal at the clearance height of 10 metres, which must be kept free for shipping.

The design's lightness is due to the stress ribbon bridge's support structure, which has been reduced to a minimum. Two high-strength steel bands connect to the two inclined supports across the canal; the resulting tensile force is transferred through outer vertical tension rods into the abutments. The 406 metre long bridge's walkway is a springy synthetic surface in 16 different colours bolted on to prefabricated concrete plates, to which the bridge's railings and spirals are attached. The steel post and cable mesh railing effectively contributes to

damping vibrations in this lively bridge. Users' dynamic experience of the bridge is emphasised by its spirals, which are set at varying distances from each other, making the bridge resemble the famous spiral toy (Slinky). However, the serpentine structure only really unfolds its full effect in darkness. LEDs concealed in the handrail bathe the coloured surface in an even light. Seen from below, the bridge glows in bright colours. Lights integrated into the spirals also illuminate the bridge's underside.

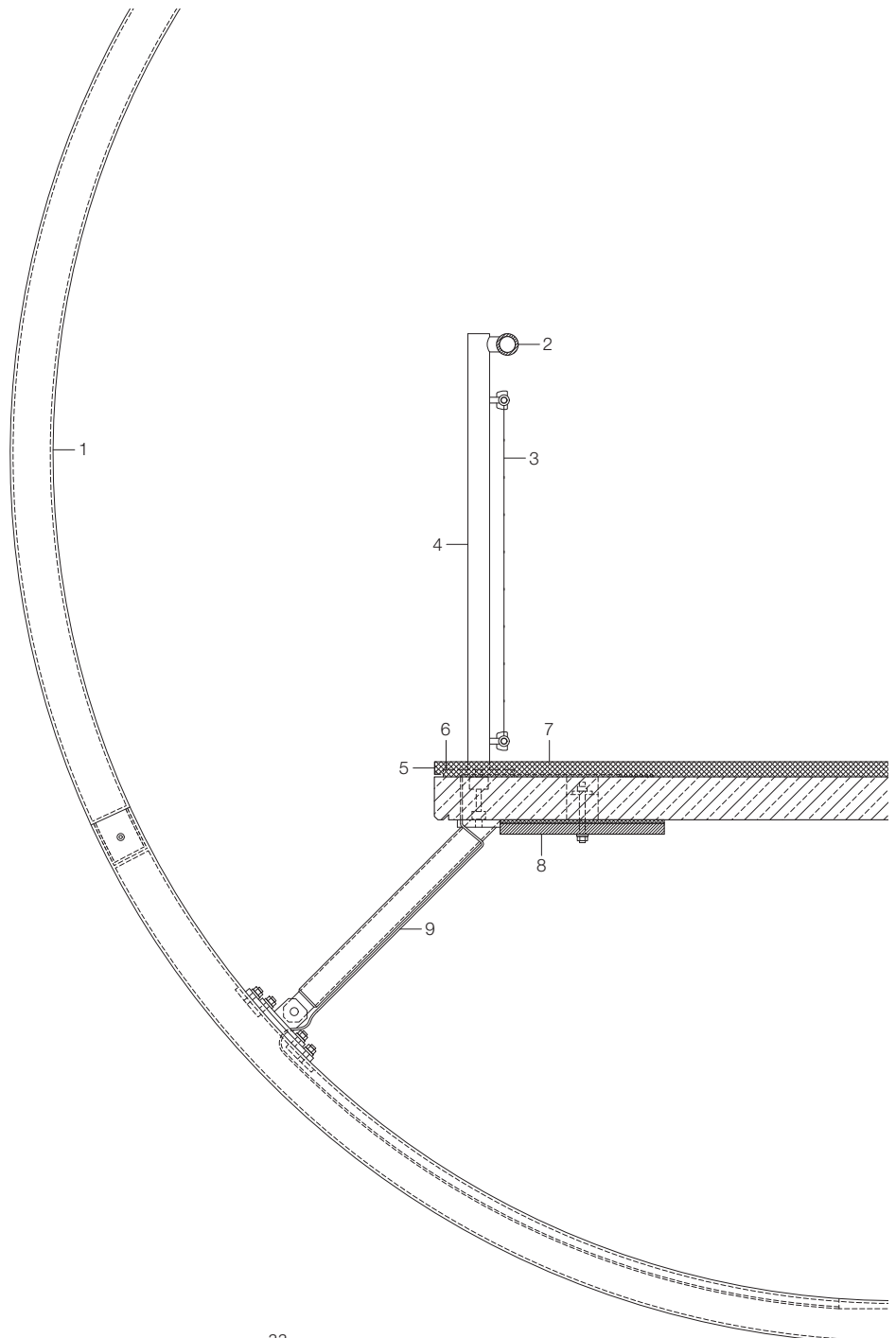
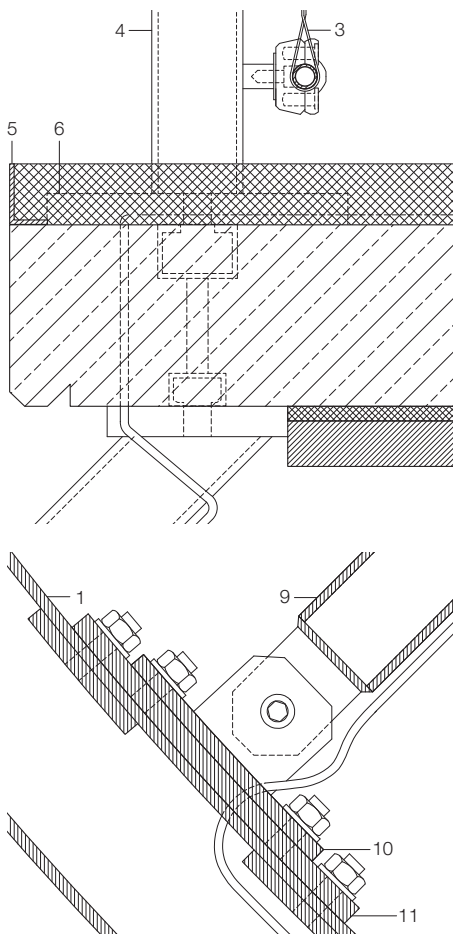




Structure: Stress ribbon bridge  
 Material: Steel  
 Total length: 406 m  
 Ramp length: 130 and 170 m  
 Span length: 20 /66 /20 m  
 (Stress ribbon bridge)  
 Width: 2.67 m  
 Bridge surface area: 1,085 m<sup>2</sup>  
 Superstructure height: 12 cm (Stress ribbon bridge)

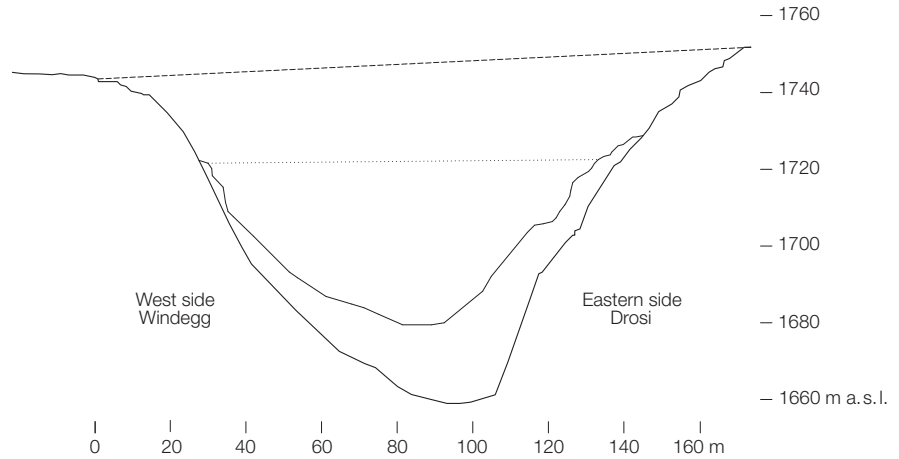
Site plan Scale 1:1500  
 Details bridge superstructure and spiral connectors – strut Scale 1:5  
 Vertical section Scale 1:20

- 1 Spiral aluminium tube  $\square$  80/80/2 mm
- 2 Handrail, stainless steel tube  $\varnothing$  60,3/4 mm
- 3 Railing: stainless steel mesh  $\varnothing$  2 mm, mesh size 60/104 mm, on stainless steel tube  $\varnothing$  20/1,5 mm
- 4 Posts with cable routing, steel tube  $\varnothing$  60,3/8 mm
- 5 Steel profile L 40/25/3 mm
- 6 Base plate, flat steel  $\square$  15 mm
- 7 Surface, PU-bound EPDM virgin rubber granulate on reinforced concrete prefabricated parts 120 mm
- 8 Stress ribbon, steel 460/30 mm
- 9 Strut, steel tube  $\varnothing$  76,1/5 mm
- 10 Connecting plate, flat steel  $\square$  20 mm
- 11 Counter plate, flat steel  $\square$  15 mm



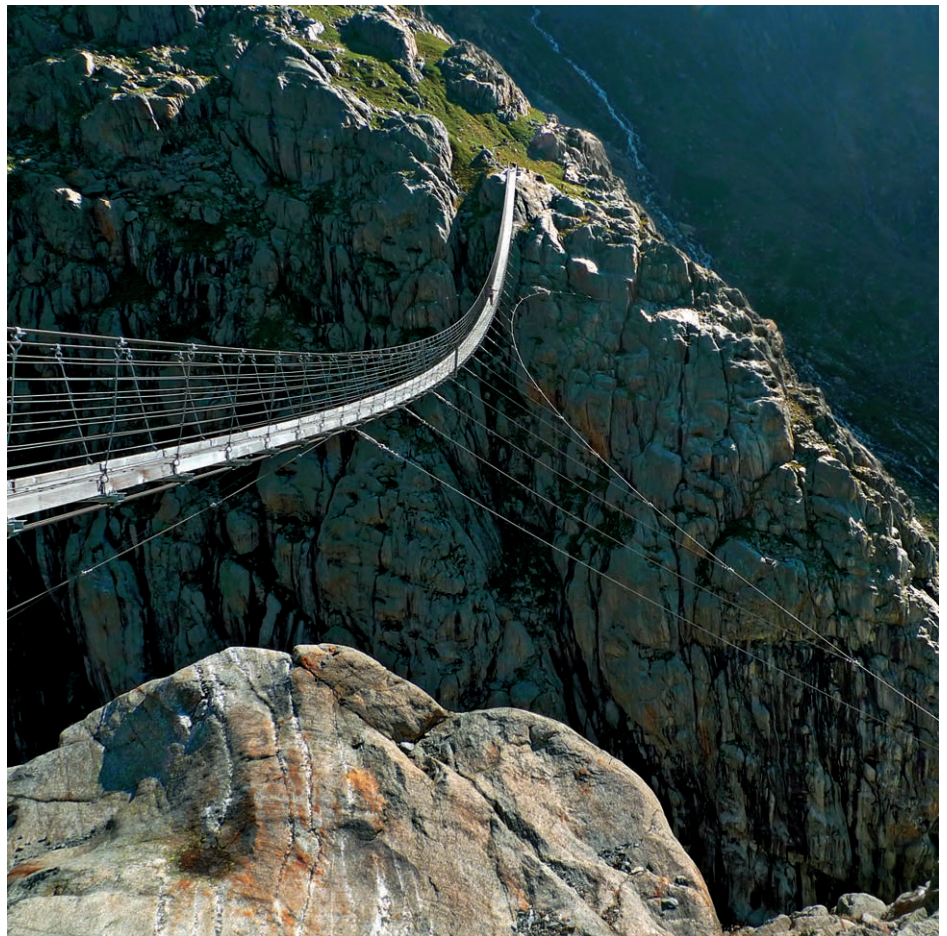
## Bridge on Trift Glacier (CH)

Structural designer: Ingenieurbüro Hans Pfaffen,  
Chur  
Project manager: Walter Brog, x-alpin,  
Innertkirchen  
Completed: 2009



On the Trift Glacier near Switzerland's Susten Pass – one of the fastest-melting glaciers in the Alps – the first Trift Bridge opened in September 2004. It was however, built on a site not easily accessible to visitors. Given the large increase in visitor numbers, it was decided to build a new bridge in a more secure location, 20 m to the north and 30 m higher. This would be easier to climb up to and thanks to the broader opening of the ravine, the wind speeds there would also be lower. The construction principle remained the same but underwent some crucial adjustments, partly due to the longer span. Parabolic underspanning reinforces the slender structure and prevents lifting in extreme wind speeds. Pylons and two U-shaped steel elements a third of a way along the span further stabilise the railings at parapet height at their terminals and reinforce the bearer cables.

After two years of planning, the new 170 metre long bridge, which spans the Triftwasser stream just 100 m above it, was built over six weeks in the summer of 2009. During construction, the old bridge served as a work platform, during delivery of the bearer cables by helicopter, for example. After they were deeply anchored in granite using threaded rods and tensioned, a small, sliding work gondola could be placed on them and was used to install the crossbeams, walkway planks and parapet elements, step by step. The arch-shaped underspanning was then installed. Only after this work was completed was the old bridge dismantled and erected in its new site. It is now called the »Salbit Bridge« and links two mountain huts in the nearby Göschener Valley.



Section Trift Ravine  
Scale 1:2000  
..... 1st Trift Bridge site, 2004  
--- 2nd Trift Bridge site, 2009

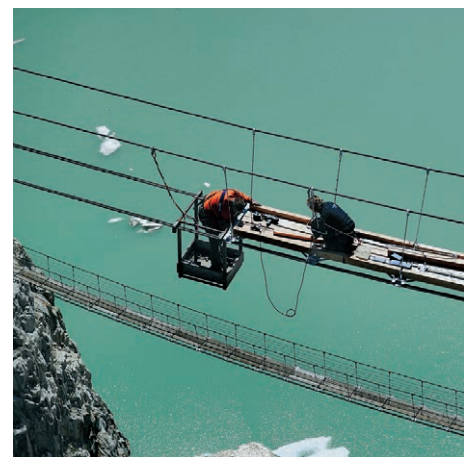
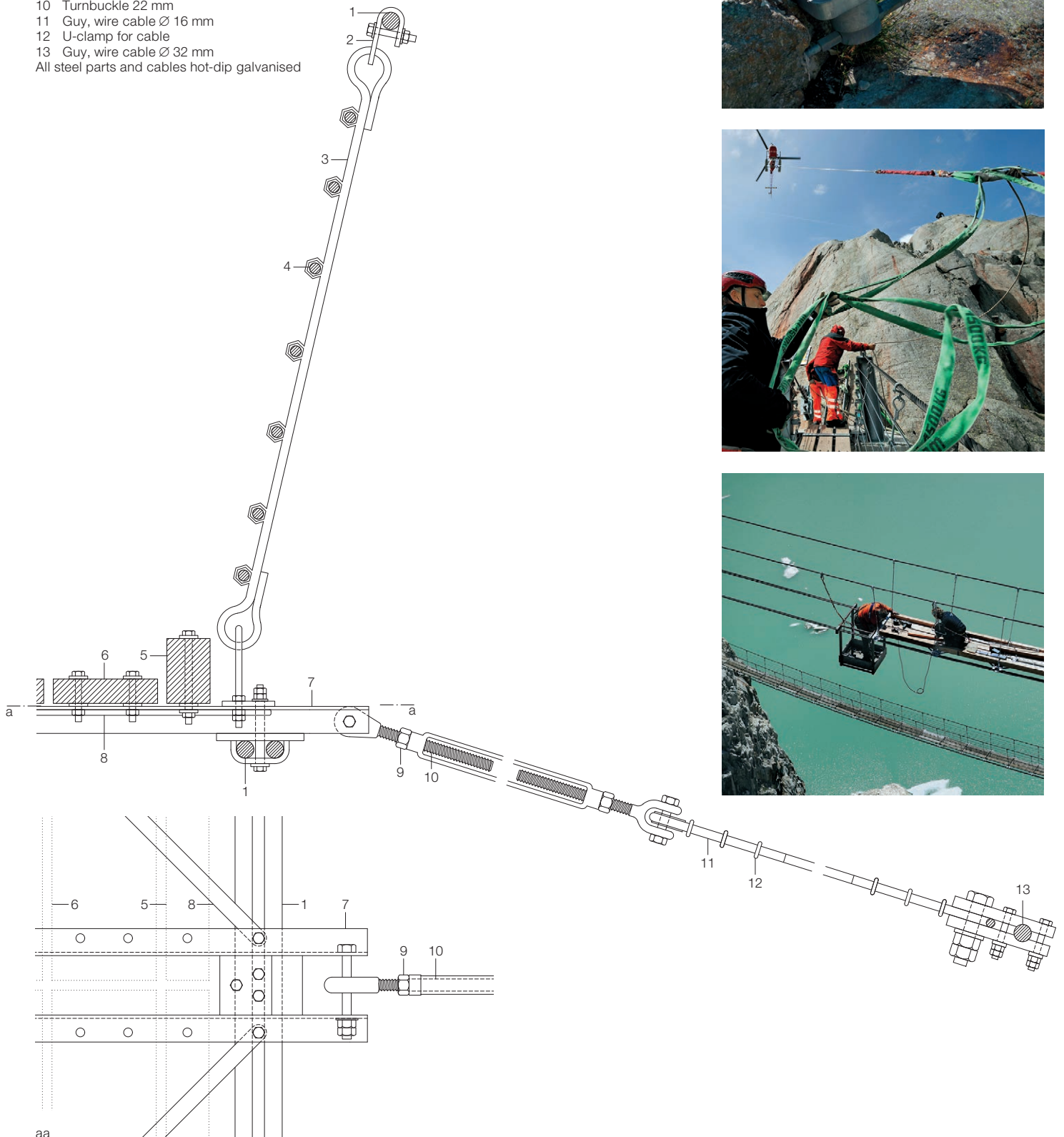
Section  
Scale 1:50



Vertical section • Horizontal section Scale 1:10

- 1 Wire cable, load-bearing  $\varnothing$  32 mm
  - 2 Bracket, flat steel, bent
  - 3 Steel rod with screw nuts welded on
  - 4 Parapet, wire cable
  - 5 Walkway edging, squared timber, larch, rough-sawn 80/120 mm
  - 6 Walkway, larch planks rough-sawn 200/45 mm, for structural wood protection, spaced
  - 7 Pairs of cross beams: steel profile L 50/50 mm
  - 8 Diagonal struts, flat steel
  - 9 Lock nut, bonded
  - 10 Turnbuckle 22 mm
  - 11 Guy, wire cable  $\varnothing$  16 mm
  - 12 U-clamp for cable
  - 13 Guy, wire cable  $\varnothing$  32 mm
- All steel parts and cables hot-dip galvanised

Structure: Reinforced stress ribbon bridge  
 Material: Steel  
 Total length: 168.24 m  
 Span length: 101.60 m  
 Width: 88 cm  
 Bridge surface area: 148 m<sup>2</sup>  
 Superstructure height: 25 cm

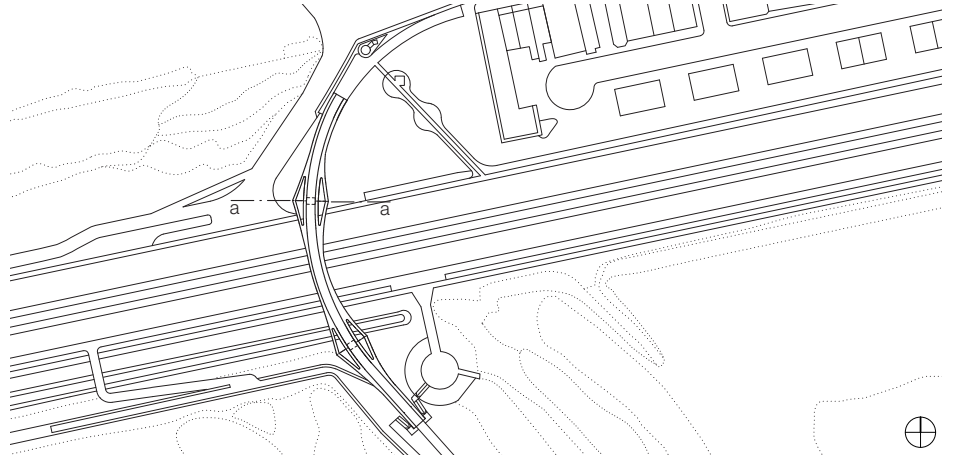


## Pedestrian and cyclist bridge in Knokke-Heist (B)

Structural designer: Ney & Partners, Brussels  
Team: Laurent Ney, Eric Bodarwé,  
Nicolas De Breuck  
Completed: 2007

Arching over busy Queen Elisabeth Avenue, this pedestrian and cyclist bridge links the North Sea bay of Heist with the Zwin nature reserve. In an elegant curve, the 102 metre long bridge winds above a four-lane road and tram line, marking the entry into the city of Knokke-Heist.

The bridge's light, floating form is impressive and naturally fits in with its environment. Ramps at each end connect with pre-existing route trajectories and lead up to the structure, which was designed as a suspension bridge.

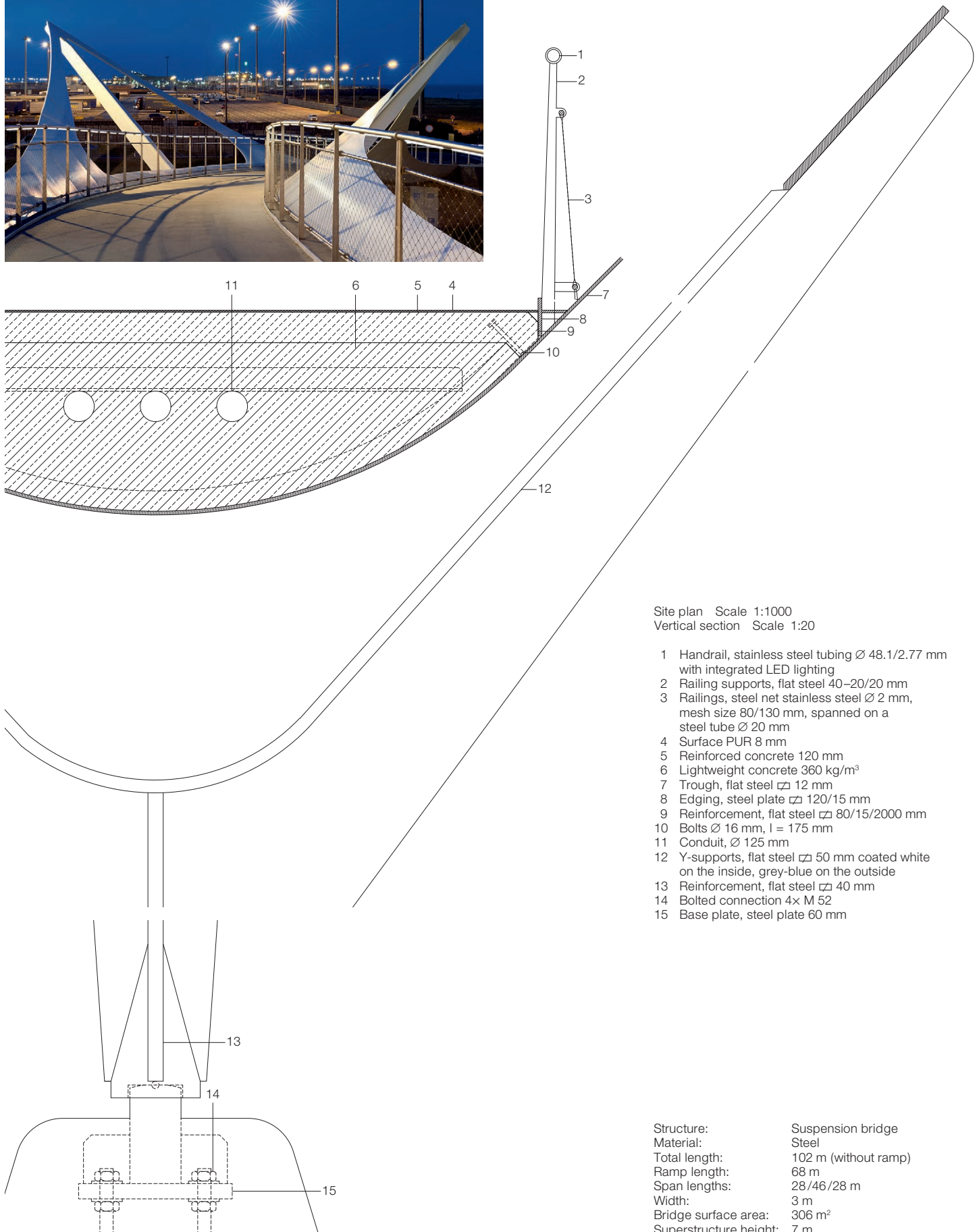


Various materials and static systems were trialed during the design phase with the aim of producing a shape as delicate as possible. A computer programme calculated the openings' optimum position and size. The result is a sculptural form that follows the course of forces and is supported on two Y-shaped supports 46 metres apart. The superstructure consists of 12 mm thick steel plates welded together and held up by the Y-supports, a bit like a hammock. This crescent-shaped steel structure continues the reinforced concrete pedestrian

and cycle path with its slip-resistant PU coating. The suspended structure's openings also accommodate vehicle traffic, providing drivers driving under it with an unobstructed view.

To make installation easier, most of the structure was prefabricated and assembled on site using slip joints. Several layers of coating – white on the inside, grey-blue on the outside – protect the steel structure from the corrosive effect of the salty North Sea air. Its railing posts and handrail are made of stainless steel tubing.





aa

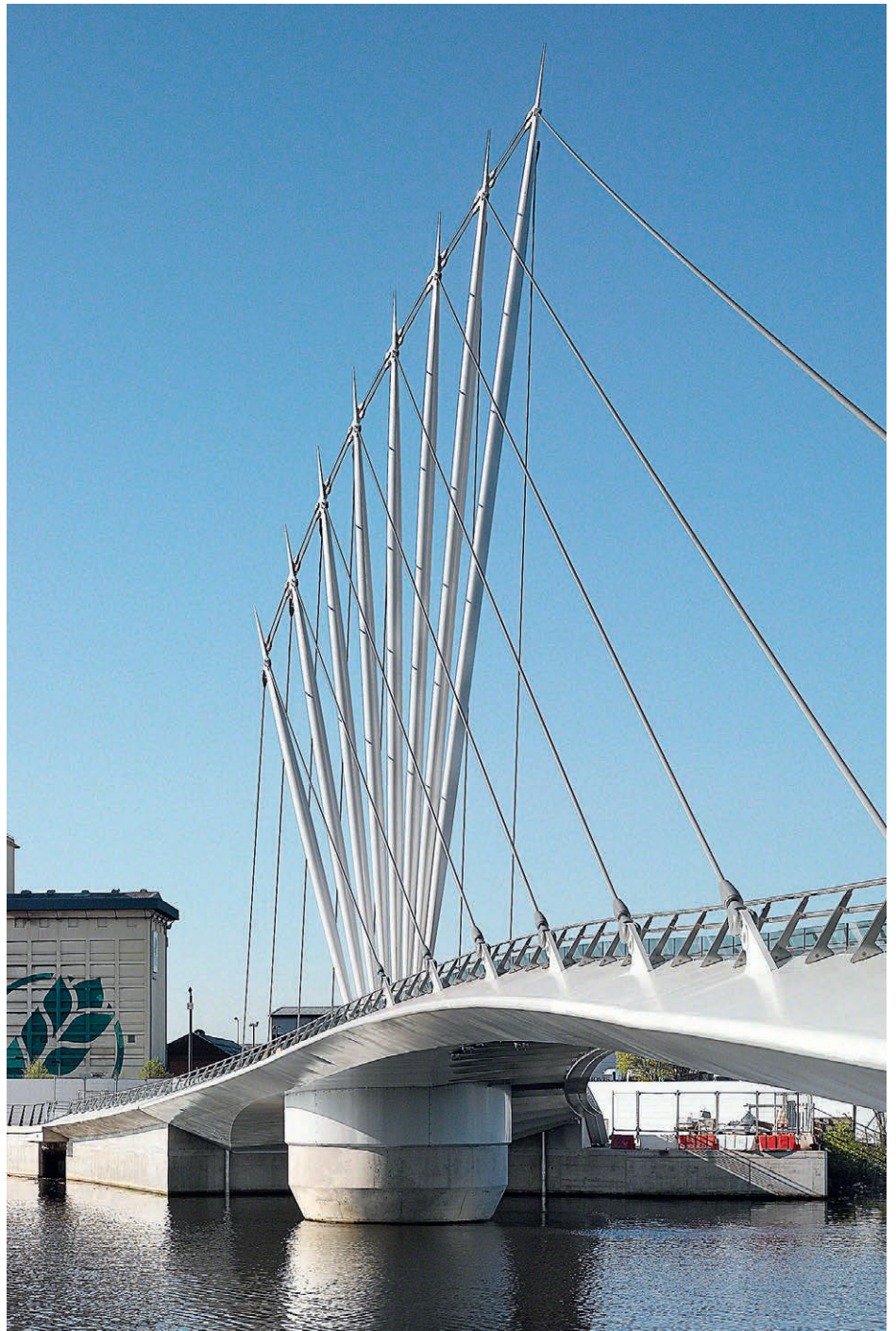
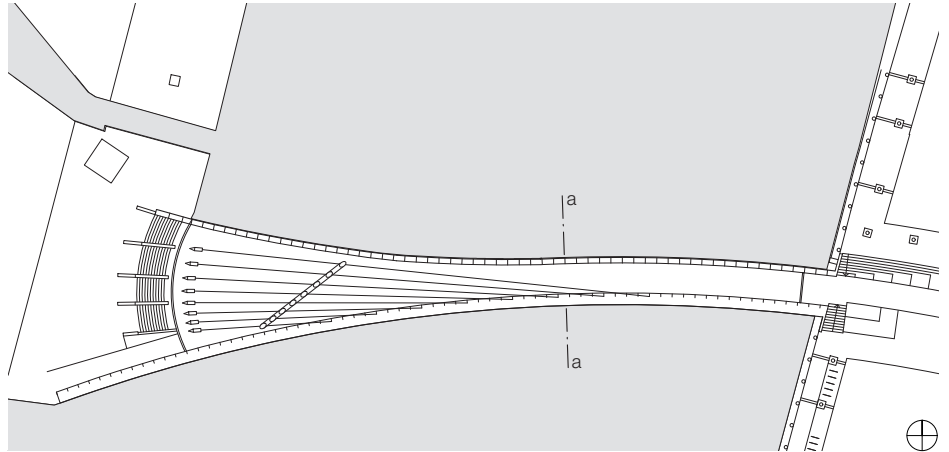
## Media City Footbridge in Salford (GB)

Architects: Wilkinson Eyre Architects, London  
Team: Chris Wilkinson, James Marks, Simon Roberts, Ezra Groskin, Connor Worth  
Structural designer: Ramboll UK, Southampton  
Team: Peter Curran, Steve Thompson  
Completed: 2011

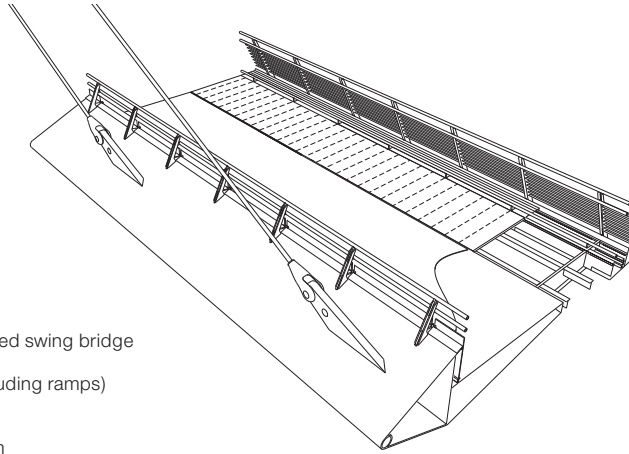
A pedestrian bridge over the Manchester Ship Canal in Salford links the Media City with the Imperial War Museum. Media City, an ambitious urban planning concept, was built on the old Salford Quays site to the west of Manchester, where there were still loading cranes and container ships until the docks closed in 1982.

A pivoting cable-stayed bridge was built to enable ships with high superstructures to pass along the canal unimpeded. The bridge, with a span of 83 metres, consists of a main cantilever arm that is 65 metres in length and an 18-metre-long auxiliary arm. The latter fans out in the direction of the Imperial War Museum, creating a public space that can be used in a variety of ways. It also forms a counterweight to the main cantilever arm. To open the bridge, its moveable part in plan is turned 90 degrees, opening up a navigation channel approximately 48 metres wide and with no height restrictions. Eight high-tensile cables running over tilt-mounted masts up to 30 metres high connect the two cantilever arms with each other. Each tension cable is set at a specific angle to the horizontal plane and rotates tangentially to the curved superstructure, producing the bridge's three-dimensional turning.

The slightly curved superstructure consists of a closed massive steel box girder, to which the anchorings of the stay cables are attached, and a filigree part, which is attached to the box girder via the cantilever arm. This division reduces the structure's weight and has static advantages. Both abutment side walls are slightly angled, which makes the structure look very slender and elegant.

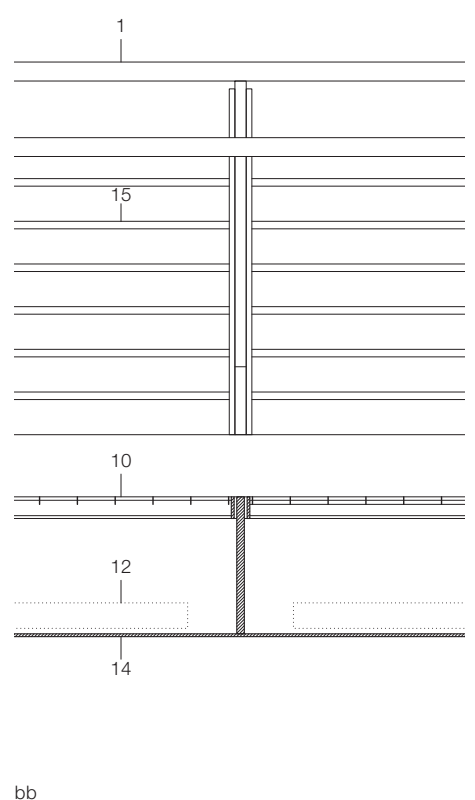
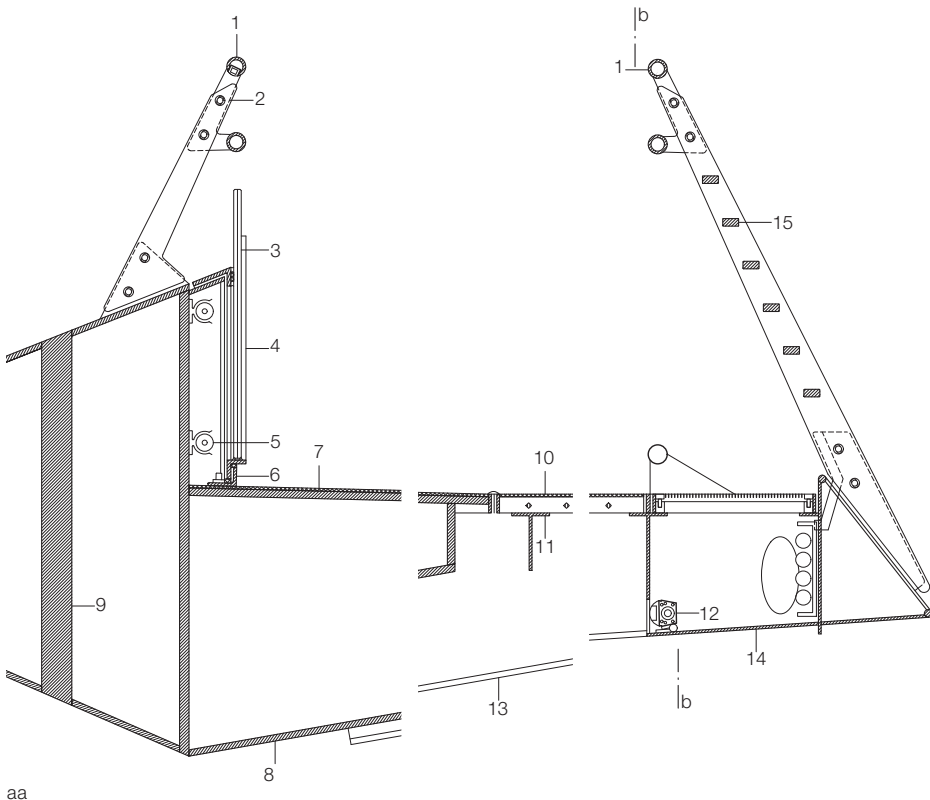


Site plan Scale 1:1000  
Axonometric main bridge arm  
Vertical section Scale 1:20



Structure: Cable-stayed swing bridge  
Material: Steel  
Total length: 83 m (excluding ramps)  
Spans: 65 m/18 m  
Width: 4 m  
Superstructure height: 1.25–0.4 m

- 1 Handrail, stainless steel tubing  $\varnothing$  50 mm
- 2 Railing supports, flat steel  $2 \times \varnothing$  10 mm
- 3 Parapet, VSG 13.5 mm transparent upper, translucent underside
- 4 Frames, steel section L 40/40 mm
- 5 Lights under acrylic glass covers
- 6 Stainless steel section L 48/72 mm
- 7 Surface, slip-resistant epoxy resin
- 8 Box girder 1250–2400 mm, flat steel, fully welded  $\varnothing$  20 mm
- 9 Reinforcement, flat steel  $\varnothing$  44/2,400 mm
- 10 Aluminium element 1,440/2,000/50 mm
- 11 Steel section T 140/100/6 mm
- 12 LED lights that change colour
- 13 Cantilever arm, flat steel  $\varnothing$  3,650/15 mm
- 14 Flat steel  $\varnothing$  15 mm
- 15 Railing rods, steel section 1,480/42/20 mm

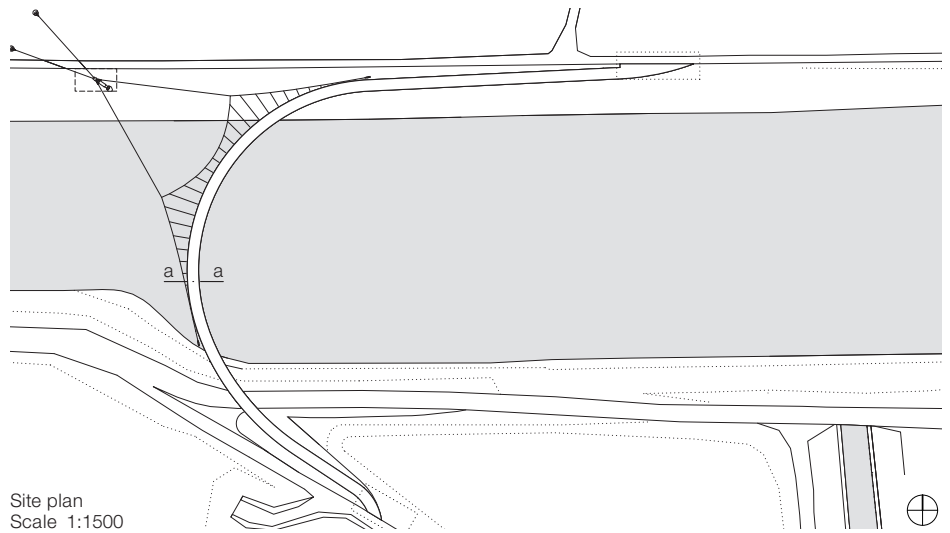


aa

bb

**Cyclist and pedestrian bridge,  
Hafen Gimberg (Gimberg Port) in  
Gelsenkirchen (D)**

Structural designer: schlaich bergemann and partners, Stuttgart  
 Team: Andreas Keil, Sebastian Linden, Sandra Hagenmayer, Roman Kemmler, Mathias Widmayer  
 Completed: 2009



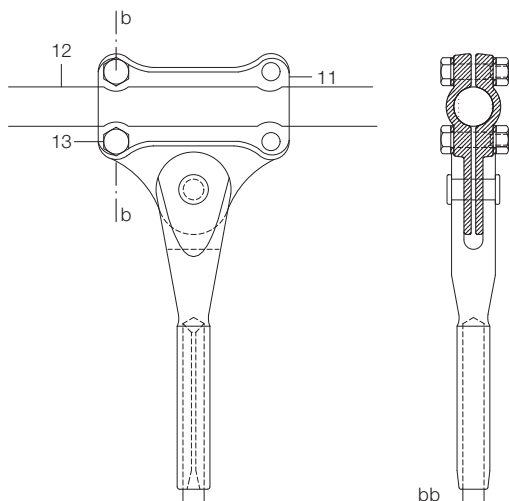
In 2006, the Ruhr Regional Association (Regionalverband Ruhr) launched a competition to design a new bridge connecting the Erzbahntrasse cycle route with the Emscher Park bike path over the Rhine-Herne Canal. The winners convinced the competition judges with a design for an innovative suspension bridge structure that crosses the canal in a single broad sweep. The bridge's circular trajectory fits in with the existing network of paths, creating the precondition for this asymmetric suspension bridge, which elegantly and concisely marks the end of Erzbahntrasse.

The bridge features a unilaterally hung ring girder with a span of 141 m between its abutments. With a single tensioned 45 m high pylon standing to one side, the superstructure, a torsionally stiff box girder, seems to float over the landscape – a unique experience for those passing by or crossing the bridge.

Support cables are arranged around a circle with hangers spaced 3 m apart and tangentially anchored in the curved superstructure. The support cables of a back-anchored suspension bridge usually pass through the superstructure

into the abutments and are anchored there. Here however, the support cable is unsupported and is anchored 24 m away from the abutments. The steel box girder is therefore monolithically connected to the abutments and of a size to bear torsional and bending loads. With a structural depth of just 80 cm, it forms the 'backbone' of the bridge deck and bears the 12 cm thick concrete slab. The slab serves as a robust walking surface and its weight improves the bridge's dynamic behaviour. A sheer cable mesh railing underscores the bridge's lightness and delicacy.

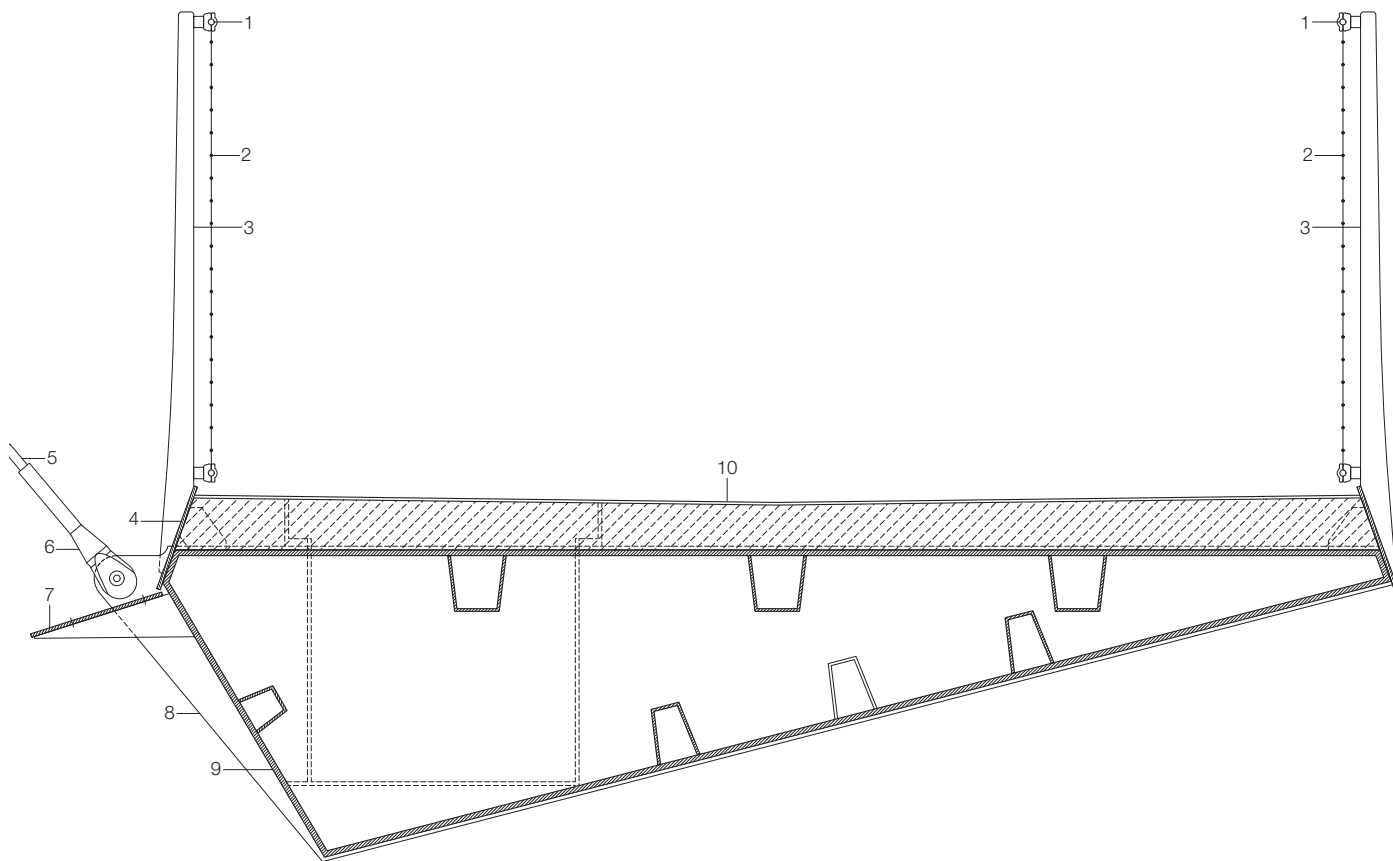




Structure: Curved suspension bridge  
Material: Steel  
Total length: 156 m (excluding ramps)  
Ramp length: 37 m (North)  
Span: 141 m  
Width: 3 m  
Bridge surface area: 579 m<sup>2</sup>  
Superstructure height: 80 cm  
Mast height: 40 m (+ 5 m mast head)

Detail section, hanger clamp Scale 1:10  
Vertical section Scale 1:20

- 1 Boundary cable, stainless steel  $\varnothing$  16 mm
- 2 Railings, stainless steel mesh  $\varnothing$  2 mm, mesh size 60 mm
- 3 Railing posts, flat steel  $\sphericalangle$  30 mm
- 4 Side plate as cover, flat steel  $\sphericalangle$  10 mm
- 5 Hangers  $\varnothing$  24 mm
- 6 Fork fitting with eye plates connected to ribs
- 7 Stainless steel sheeting  $\sphericalangle$  10 mm screwed to a steel bracket  $\sphericalangle$  15 mm, welded to the box girder
- 8 Ribs, steel plate 15 mm
- 9 Box girder, steel plate  $\sphericalangle$  15–40 mm  
Thin film surface 5 mm  
Concrete walkway slab 120 mm
- 10 Cable clamp, milled
- 12 Garland-shaped cable  $\varnothing$  50 mm
- 13 Screws M 24



aa

**Literature:****Reference texts and papers**

- Baus, Ursula; Schlaich, Mike: Fußgängerbrücken. Konstruktion, Gestalt, Geschichte. Basel/Boston/Berlin 2007
- Baus, Ursula; Schlaich, Mike: Footbridges. Construction, Design, History. Basel/Boston/Berlin 2007
- Bühler, Dirk: Brückenbau im 20. Jahrhundert. Gestaltung und Konstruktion. Munich 2004
- Dietrich, Richard J.: Faszination Brücken. Baukunst, Technik, Geschichte. Munich 2001
- Fördergemeinschaft Gutes Licht (Hrsg.): licht . wissen 03: Straßen, Wege und Plätze. Frankfurt am Main 2000
- Fördergemeinschaft Gutes Licht (pub.): Good lighting for safety on roads, paths and squares. Frankfurt am Main 2000
- Heinemeyer, Christoph et. al.: Design of Lightweight Footbridges for Human Induced Vibrations. JRC Scientific and Technical Reports. 2009
- Idelberger, Klaus, The World of Footbridges, Berlin 2011
- International Federation for Structural Concrete (pub.): Guidelines for the Design of Footbridges. Lausanne 2005
- Mostafavi, Mohsen (pub.): Structure as Space. Engineering and Architecture in the Works of Jürg Conzett and his Partners. London 2006
- Ney, Laurent; Adriaenssens, Sigrid: Shaping Forces. Brussels 2010
- Pearce, Martin; Jobson, Richard: Bridge Builders. Chichester 2002.
- Petersen, Christian: Schwingungsdämpfer im Ingenieurbau. Munich 2001
- RWTH Aachen et al.: Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008
- RWTH Aachen et al.: Human Induced Vibrations of Steel Structures. Leitfaden für die Bemessung von Fußgängerbrücken (HIVOSS). 2008
- Service d'Études Techniques des Routes et Auto routes – SETRA (pub.): Footbridges – Assessment of Vibrational Behaviour of Footbridges under Pedestrian Loading. Paris 2006
- Strasky, Jiri: Stress Ribbon and Cablesupported Pedestrian Bridges. London 2011

**Standards, guidelines, regulations (a selection)**

- DIN 1076 Highway structures – Testing and Inspection. 1999-11
- DIN 18024-1 Barrier-free built environment – Part 1: Streets, squares, paths, public transport, recreation areas and playgrounds – Design principles. 1998-01
- DIN 18065 Stairs in buildings – Terminology, measuring rules, main dimensions. 2011-06
- DIN 68800-1 Wood preservation – Part 1: General. 2011-10
- DIN 68800-2 Wood preservation – Part 2: Preventive constructional measures in buildings
- DIN 68800-3 Wood preservation – Part 3: Preventive protection of wood with wood preservatives
- DIN EN 350-1 Durability of wood and wood-based products – Natural durability of solid wood – Part 1: Guide to the principles of testing and Classification of the natural durability of wood
- DIN EN 350-2 Durability of wood and wood-based products – Natural durability of solid wood – Part 2: Guide to the natural durability and treatability of selected wood species of importance in Europe
- DIN EN 1090-1 Execution of steel structures and aluminium structures – Part 1: Requirements for conformity assessment of structural components. 2012-02
- DIN EN 1090-2 Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures. 2011-10
- DIN EN 1090-3 Execution of steel structures and aluminium structures - Part 3: Technical requirements for aluminium structures. 2008-09
- DIN EN 1337-1 Structural bearings – Part 1: General design rules. 2001-02
- DIN EN 1337-2 Structural bearings – Part 2: Sliding elements. 2004-07
- DIN EN 1337-3 Structural bearings – Part 3: Elastomeric bearings. 2005-07
- DIN EN 1337-4 Structural bearings – Part 4: Roller bearings. 2007-05
- DIN EN 1337-5 Structural bearings – Part 5: ot bearings. 2005-07
- DIN EN 1337-6 Structural bearings – Part 6: Rocker bearings. 2004-08
- DIN EN 1337-7 Structural bearings – Part 7: Spherical and cylindrical PTFE bearings. 2004-08
- DIN EN 1337-8 Structural bearings – Part 8: Guide Bearings and Restraint bearings. 2008-01
- DIN EN 1337-9 Structural bearings – Part 9: Protection. 1998-04
- DIN EN 1337-10 Structural bearings – Part 10: Inspection and maintenance. 2003-11
- DIN EN 1337-11 Structural bearings – Part 11: Transport, storage and Installation. 1998-04
- DIN EN 1990 Eurocode: Basis of structural design. 2012-08
- DIN EN 1991-1-1 Eurocode 1: General actions on structures – Part 1-1: Densities, self-weight, imposed loads for buildings. 2010-12
- DIN EN 1991-2 Eurocode 1: General actions on structures – Part 2: Traffic loads on bridges. 2012-08
- DIN EN 1992-1-1 Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings. 2012-05
- DIN EN 1992-2 Eurocode 2: Design of concrete structures – Part 2: Concrete bridges – Design and detailing rules. 2012-04
- DIN EN 1993-1-1 Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings. 2010-12
- DIN EN 1993-2 Eurocode 3: Design of steel structures – Part 2: Steel bridges. 2012-08
- DIN EN 1994-1-1 Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings. 2010-12
- DIN EN 1994-2 Eurocode 4: Design of composite steel and concrete structures – Part 2: General rules and rules for bridges. 2010-12
- DIN EN 1995-1-1 Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings. 2012-02
- DIN EN 1995-2 Eurocode 5: Design of timber structures – Part 2: Bridges. 2011-08
- DIN EN 13201-1 Road lighting – Part 1: Selection of lighting classes. 2005-11
- DIN EN 13201-2 Road lighting – Part 2: Performance requirements. 2004-04
- DIN EN 13201-3 Road lighting – Part 3: Calculation of performance. 2004-04
- DIN EN 50122-1 Railway applications – Fixed installations – Electrical safety, earthing and the return circuit – Part 1: Protective provisions against electric shock. 2011-09
- DIN EN ISO 12944 Paints and varnishes – Corrosion protection of steel structures by protective paint systems. 1998–2008
- DIN Technical rule 101 Actions on bridges
- DIN Technical rule 102 Concrete bridges
- DIN Technical rule 103 Steel bridges
- DIN Technical rule 104 Composite steel and concrete bridges
- Bundesanstalt für Straßenwesen (pub.): Richtzeichnungen für Ingenieurbauten (RiZ-ING). 2012-03
- Bundesanstalt für Straßenwesen (pub.): Technische Lieferbedingungen und Technische Prüfverfahren für Ingenieurbauten (TL/TPING). 2010-04
- Bundesanstalt für Straßenwesen (pub.): Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING). Teil 3: Massivbau. 2010-04
- Bundesanstalt für Straßenwesen (pub.): Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING). Teil 4: Stahlbau, Stahlverbundbau. 2003-01
- Bundesanstalt für Straßenwesen (pub.): Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING). Teil 7: Brückenbeläge. 2003-01
- Bundesanstalt für Straßenwesen (pub.): Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING). Teil 8: Bauwerksausstattung. 2010-04
- Bundesminister für Verkehr (pub.): Richtlinien für den Korrosionsschutz von Seilen und Kabeln im Brückenbau (RKS-Seile). Dortmund 1984
- Deutsche Bahn AG (pub.): Richtlinie (Ril) 997.0101 Oberleitungsanlagen. Allgemeine Grundsätze. 2001-01
- Deutsche Bahn AG (pub.): Richtzeichnungen. 3 Ebs 02.05.19, Berührungsschutzmaßnahmen. Deutsches Institut für Bautechnik (pub.): Technische Regeln für die Verwendung von absturzsichernden Verglasungen (TRAV). 2003
- Deutsches Institut für Bautechnik (pub.): Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen (TRLV). 2006
- Forschungsgesellschaft für Straßen und Verkehrswesen (pub.): Empfehlungen für Fußgängerverkehrsanlagen (EFA). Cologne 2002
- Forschungsgesellschaft für Straßen- und Verkehrswesen (pub.): Empfehlungen für Radverkehrsanlagen (ERA). Cologne, 2010
- Forschungsgesellschaft für Straßen- und Verkehrswesen (pub.): Merkblatt über den Rutschwiderstand von Pflaster und Plattenbelägen für den Fußgängerverkehr. Cologne, 1997
- Hauptverband der gewerblichen Berufsgenossenschaften (pub.): BGR 181 Fußböden in Arbeitsräumen und Arbeitsbereichen mit Rutschgefahr. 2003-10

## Picture credits

To everyone who has helped with putting this book together, through licensing their pictures, giving permission for reproduction and through providing information, the authors and publishers would like to say a sincere thank you. All of the drawings in this book have been created in-house. Pictures without credits come from the archive of the architects or from the archive of DETAIL journal. Despite intensive efforts we were not able to determine some of the creators of the photos and images, however, their copyrights are protected. We would ask you to keep us informed accordingly.

- Pages 7, 40 FG + SG Fotografia de Architectura, P–Lisbon
- Page 9 from International Federation for Structural Concrete (pub.): Guidelines for the Design of Footbridges. Lausanne 2005, p. 11
- Page 10 top left, top centre, above right Elsa Caetano, P–Porto
- Page 10 centre from Bundesministerium für Verkehr, Bau und Stadtentwicklung – BMVBS (pub.): Forschung Straßenbau und Straßenverkehrstechnik. 22/1963, p. 3
- Page 11 top from RWTH Aachen et al.: Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008
- Page 12 left Lukas Roth, D–Cologne
- Page 12 right Stahlbau Urfer, D–Remseck (Aldingen)
- Page 13 Hertha Hurnau, A–Vienna
- Page 14 top, 31 below left, 34, 49 below right, 51, 52 below, 59 top, 63, 67 top left, top centre, 73 top left, top right, 75 top centre, 88 below, right schlaich bergemann and partners, D–Stuttgart
- Page 14 above Christian Richters, D–Münster
- Page 14 below Jens Markus Lindhe, DK–Copenhagen
- Page 14 bottom, 92, 93 below left, below centre, below right Christian Vogel, D–Munich
- Page 15 above, below from Bundesanstalt für Straßenwesen (pub.): Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTVING). Part 8: Bauwerksausstattung, Section 4: Absturzsicherungen. 2010, p. 3
- Page 16 Christian Schittich, D–Munich
- Page 17 from, International Federation for Structural Concrete (pub.): Guidelines for the Design of Footbridges. Lausanne 2005, p. 24
- Page 18 above from International Federation for Structural Concrete (pub.): Guidelines for the Design of Footbridges. Lausanne 2005, p. 15
- Page 18 below Wacker Ingenieure, D–Birkenfeld
- Page 19 from DIN Fachbericht 101 Einwirkungen auf Brücken. 2009, p. 122
- Page 20 left from DIN Fachbericht 101 Einwirkungen auf Brücken. 2009, p. 132
- Page 20 right, 25 Gerb Schwingungsisolierungen GmbH & Co. KG, D–Berlin
- Page 23 above from International Federation for Structural Concrete (pub.): Guidelines for the Design of Footbridges. Lausanne 2005, p. 31f.
- Page 24 above from RWTH Aachen et al.: Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008, p. 29
- Page 24 top left, 48, 49 above left, above right, 75 top Gert Elsner, D–Stuttgart
- Page 24 above left from RWTH Aachen et al.: Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008, p. 13
- Page 24 lower left seggel/www.pfnz.de/wiki/Wachtelsteg
- Page 24 bottom left from RWTH Aachen et al.: Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Foot Bridges (SYNPEX). 2008, p. 14
- Page 26, 54, 55 below Alan Karchmer/Esto, New York, USA
- Page 27 above Erhard Kargel, A–Linz
- Page 27 centre from Frank Dehn, Gert König, Gero Marzahn: Konstruktionswerkstoffe im Bauwesen. Berlin 2003, p. 14
- Page 27 below, 28 upper left after: DIN EN 350-2. 1994
- Page 28 above left Schaffitzel Holzindustrie GmbH + Co. KG, D–Schwäbisch Hall
- Page 28 centre left Sweco Norge AS
- Page 28 lower left, 50 upper left, 59 below, 71 lower right, 85 HG Esch Photography, D–Hennef
- Page 29 left maarjaara/www.wikipedia.fr
- Page 29 right Dietmar Strauß, D–Besigheim
- Page 30, 66 centre, 69 above, 84 above, 104, 105 Jean-Luc Deru, B–Liège
- Page 31 upper left www.kismile.de/kismile/view221,1,1535.html
- Page 31 upper right Achim Bleicher: Aktive Schwingungskontrolle einer Spannbandbrücke mit pneumatischen Aktuatoren. Diss., TU Berlin 2011
- Page 31 lower right Carles Teixidor/Bellapart S.A.U., E–Olot
- Page 32, 49 lower left, 50 upper right, 58 above, 61 below, 108, 109 Michael Zimmermann, D–Stuttgart
- Page 35 Franziska Andre/www.swissmountainview.ch
- Page 36 left RFR, F–Paris
- Page 36 right http://de.wikipedia.org/w/index.php?title=Datei:Dreilaenderbruecke003.jpg&filetime stamp=20081026160541
- Page 38 upper Graeme Smith/www.flickr.de
- Pages 39, 69 below Aljosa Brajdic, HR–Rijeka
- Page 43 David Humphry/www.flickr.de
- Page 45 centre Jeannette Tschudy, CH–Chur
- Page 45 below, 70 Ros Kavanag/VIEWpictures.co.uk
- Page 46 above Ian Harding, CDN–Calgary
- Page 46 below left Chris Gascoigne, GB–London
- Page 46 below right Paul McMullin, GB–Aughton
- Page 47 Manfred Gerner, D–Fulda
- Page 50 below from www.pfeifer.de
- Page 52 above, from Mike Schlaich, Ursula Baus: Fußgängerbrücken. Basel/Boston/Berlin 2007, p. 119
- Page 52 centre, 56 below, 62 above, 73 below, 76 Wilfried Dechau, D–Stuttgart
- Page 53 N. Koshhofer/Archiv Kiedrowski, D–Ratingen
- Page 55 above Gabriele Basilio, I–Milan
- Page 56 above David Newbegin/www.flickr.de
- Pages 57, 102, 103 above Thomas Madlener, D–Munich
- Page 58 below, 98, 99 left, right Richard J. Dietrich, D–Traunstein
- Page 60 Shigeyama/www.flickr.de
- Page 62 below left, Thomas Riehle, D–Bergisch Gladbach
- Page 62 below right, Jürgen Schmidt, D–Cologne
- Page 64 Roland Halbe, D–Stuttgart
- Page 67 upper right, 100, 101 Roman Mensing, D–Münster
- Page 67 below Palladium Photodesign/Barbara Burg + Oliver Schuh, D–Cologne
- Pages 68, 96 Richard Davies, GB–London
- Page 71 upper right from www.mauerssoehne.de/bauwerkschutzsysteme/dehnfugen
- Page 72 upper left, upper right, centre mageba sa, CH–Bülach
- Pages 74, 75 below 3LHD, HR–Zagreb
- Page 75 lower centre Rene Pelzer, D–Simmerath
- Page 80 from top to bottom: schlaich bergemann and partners, D–Stuttgart  
HG Esch Photography, D–Hennef  
David Boureau, F–Paris  
Michael Zimmermann, D–Stuttgart  
Lukas Roth, D–Cologne  
Ros Kavanag/VIEWpictures.co.uk  
Roman Mensing, D–Münster  
HG Esch Photography, D–Hennef  
schlaich bergemann and partners, D–Stuttgart  
Adrian Pingston/www.wikipedia.de  
Ingrid Fiebak, D–Leer
- Page 81 from top to bottom: HG Esch Photography, D–Hennef  
Tomas Riehle/www.tomasriehle.de  
schlaich bergemann and partners/  
Michael Zimmermann, D–Stuttgart  
Wilfried Dechau, D–Stuttgart  
Rob 't Hart, NL–Rotterdam  
Michael Zimmermann, D–Stuttgart  
schlaich bergemann and partners, D–Stuttgart  
http://de.wikipedia.org/w/index.php?title=Datei:Dreilaenderbruecke003.jpg&filetime stamp=20081026160541  
schlaich bergemann and partners, D–Stuttgart  
Wilkinson Eyre Architects, GB–London  
schlaich bergemann and partners, D–Stuttgart
- Page 83 Wilkinson Eyre Architects, GB–London
- Page 84 below from, Mike Schlaich, Ursula Baus: Fußgängerbrücken. Basel/Boston/Berlin 2007, p. 194f.
- Page 86 upper left WTM Engineers GmbH, D–Hamburg
- Page 86 upper right Griff Arkitektur, N–Fredrikstad
- Page 86 below Klaus Frahm, D–Cologne
- Page 87 above SKM Anthony Hunt Associates, GB–London
- Page 87 upper right, centre right, lower right Steve Speller/www.spellermlinerdesign.co.uk
- Page 88 upper left, Kurt Pock/www.pock.cc
- Page 88 centre Ignacio Martínez, E–Navia Asturias
- Page 88 upper right Thomas Jantscher, CH–Colombier
- Page 88 below left SOLID architecture ZT GmbH, Vienna, Austria
- Page 89 upper left Irene Wallmann, A–Vienna
- Page 89 below Nils Viko, CDN–Winnipeg
- Page 90 Bild KWO, photo, Robert Bösch
- Page 97 above, below RBG Kew
- Page 97 centre Richard Glover/VIEWpictures.co.uk/arturimages
- Page 103 lower centre Robert Bösch, CH–Oberägeri
- Page 106, 107 left Daniel Hopkinson, GB–Manchester

## Photos between chapters

- Page 8: Footbridge, Stuttgart (D), Kaag + Schwarz, Stuttgart
- Page 16: Millennium Bridge, London (GB) 2000, Foster + Partners, London; Sir Anthony Caro, London; Ove Arup & Partners, London
- Page 26: Bridge over the Hoofdvaart Canal, Nieuw Vennepe (NL) 2004, Santiago Calatrava, Zurich; Combinatie Dekker, Vobi van der Horst, Warmenhuizen
- Page 32: Passerelle La Défense, Paris (F) 2007, Dietmar Feichtinger Architects, Paris; schlaich bergemann and partners, Stuttgart
- Page 64: Arganzuela footbridge, Madrid (E) 2011, Dominique Perrault Architecture, Paris; MC2/Julio Martínez Calzón, Madrid; TYPSA, Madrid
- Page 76: Aaresteg, Rapperswil (CH) 2010, Conzett Bronzini Gartmann, Chur
- Page 82: Footbridge, West India Dock, London (GB) 1996, Future Systems, London; Anthony Hunt Associates, Cirencester
- Page 90: Trift Glacier bridge (CH) 2009, Ingenieurbüro Hans Pfaffen, Chur

## Index

- abutment** 34  
**acceleration** 20f., 23  
**access** 12  
**aerodynamic shape parameter cp** 18  
**aeroelastic instabilities** 19, 21  
**aluminium** 31, 65  
**anchored foundations** 51  
**arch bridges** 35ff., 92f.  
  - true 36  
  - curved 63  
  - false 36  
**assessment of vibration** 24
- barrier-free construction** 9, 13  
**beam bridges** 20, 38  
**beam, truss, support**  
  - truss girder 43ff.  
  - fish-belly truss 44  
  - lenticular truss 44  
  - parabolic truss 43  
  - Fink truss 44  
**bearing** 34, 72  
  - elastomeric bearing 40, 72  
  - ball bearing 72  
  - pendulum bearing 72  
  - point rocker bearing 72  
**bending galloping** 21  
**bending stiffness** 20  
**bollard** 50  
**bowstring arch bridge** 36f.  
**breaking length** 27  
**bridges**  
  - moveable 83ff.  
  - bridge beam 34  
  - bridge width 9  
  - bridge mass 25  
  - curved 60ff.  
  - closed 87f.  
  - integral 41f.  
  - semi-integral 41  
  - telescoping 86  
  - underspanned 47  
**butt and strap joint** 55
- cable clamps, rope clamps** 50  
**cable end connections** 50  
**cable saddle** 49  
**cable steel** 30  
**cable-stayed bridge** 57  
**capacity** 9, 33  
**capping loads** 17  
**cast steel** 30  
**clearance gauge** 11f.  
**comfort classes** 11, 24  
**comfort criteria** 23, 24  
**composite construction** 30  
**concrete** 29, 65  
**costs** 78f.  
**costs calculation** 79  
**costs estimate** 79  
**critical speed** 22
- damper elements** 19f., 25  
  - viscous dampers 25  
  - liquid column dampers 25  
  - mass dampers 25  
  - pendulum dampers 25  
  - viscous 25  
**damping** 21  
  - structure damping 21, 25  
**danger zones** 11  
**design** 33  
**design situation** 23  
**divergence** 22  
**drawbridges** 83f.  
**durability** 28  
**dynamic** 19ff.  
**dynamic vibration absorber** 25
- excitation** 20  
  - by pedestrians 23f.  
  - by wind 21f.  
**excitation frequency** 21  
**expansion joints** 70
- fairface concrete, exposed concrete** 29  
**fan arrangement** 53  
**flow capacity** 10  
**flow, flow rate** 9  
**flutter** 21f.  
**folding bridges** 84  
**foot of the mast** 55  
**furniture** 70
- galvan zinc coating** 30  
**galloping** 22  
**galvanised coating** 48  
**geometrically non-linear effects for small deformations** 35  
**glass** 31, 67
- handrail** 14, 70  
**hanger ropes, hanger cables** 49f.  
  - correction of length 50  
**harp arrangement** 53  
**heavyweight foundations** 55
- impact loads** 11, 18  
**intermediate landing** 14  
**life cycle considerations** 79  
**life cycle costs** 79  
**lifts** 13  
**lighting** 72ff.  
**loads**  
  - concentrated load 17  
  - horizontal 14, 17f.  
  - temperature loads 18  
  - traffic loads 17  
  - vertical 17  
**lock-in effect** 17, 23  
**loop anchoring** 51
- maintenance costs** 77  
**manufacturing costs** 77  
**mast head** 55  
**masts** 49, 51, 55  
**material damping** 21  
**maximum height** 27  
**measurement of vibration** 25  
**minimum width** 9ff.  
**modal mass** 20  
**modal shape** 20  
**model of a section** 23  
**multi-span cable-stayed bridge** 53ff., 106f.
- natural frequencies** 20  
**network arch bridge** 36  
**network of paths** 33  
**normal modes** 20
- own weight** 17
- piers, supports** 34  
  - rocking pier 40  
**piles** 55  
**platforms** 88f.  
**pre-stressed steel** 29  
**propulsion** 87  
**pylons** 51, 55
- railings** 14, 68  
  - stainless steel cable mesh railings 69  
  - railing infill 14  
  - railing height 14  
  - glass railing 69  
  - horizontal filled rod railing 68  
  - integrated 70  
  - chain link railings 69  
  - cable net railing 15  
  - vertical filled-rod railings 15, 68  
**ramps** 13  
**redirection** 59  
**reinforcement** 29  
**resistance classes** 27  
**resonance** 20f.  
**retaining cable, rope** 49  
**retractable bridges** 84  
**ring girder** 60  
**rise height** 37, 77
- rolling bridge** 86  
**route layout** 12ff.
- sailor's walk** 23  
**shrinkage rate** 28  
**single mass oscillator** 20  
**slab bridges** 38ff.  
**slip-resistance** 15  
**slopes** 13  
**spiral cables**  
  - open 30, 49, 54  
  - locked coil 30, 48, 54  
**stairs** 13  
**statics** 17ff.  
**stay cable** 54  
**steel** 29f., 65  
  - construction steel 29  
  - high-grade steel 30  
**step frequency** 23  
**steps** 13  
**stone arch** 28  
**stone, natural stone** 28, 67  
**stress ribbon bridges** 56ff., 98f., 100f.  
**substructure** 34  
**superstructure** 34  
**support cable anchoring, bearer cable anchoring** 50  
**support cable, bearer cable** 48f.  
**surface** 15, 65ff.  
  - aluminium 65  
  - asphalt 66  
  - concrete 65  
  - bituminous 15  
  - thin film surface 15, 66  
  - glass 67  
  - wood 66  
  - synthetic, plastic 67, 100  
  - stone 67  
**susceptibility to vibration** 18  
**suspension bridges** 47ff., 102f., 104f., 108f.  
  - multi-span 57  
  - back-anchored 47  
  - self-anchored 47  
**swing bridge** 85  
**synchronisation** 20, 23  
**synthetic, plastic**  
  - carbon fibre reinforced 31, 86  
  - glass fibre reinforced 27, 31  
  - synthetic surface 67, 100
- textile concrete** 29  
**through truss system** 44  
**tie rod** 55  
**tied arch bridge** 36  
**topography** 33  
**torsional galloping** 21  
**torsional vibrations** 22f.  
**traffic classes** 11, 24  
**traffic density** 9  
**traffic speed** 9  
**truss bridges** 43ff., 94f.  
**tuned mass dampers** 25  
**turnbuckle** 50
- underspanned systems** 43  
**underspanning** 57
- vandalism** 19  
**vibration control** 25  
**vibration meter** 25  
**vibrations** 19, 24  
  - human-induced 19  
  - self-induced 22  
  - vertical vibrations 22f.  
  - wind-induced 19  
  - turbulence-induced transverse vibrations 22
- water drainage** 71  
**wind load zones** 18  
**wind loads** 18  
**wind tunnel** 18, 22  
**wood** 27f., 45, 66  
**wood protection, treatment**  
  - chemical 28  
  - structural 28, 87



Pedestrian bridges are primarily functional, but they should also respond to the special features of their sites, route trajectories, topography and contexts. Their presence in public spaces offers an opportunity not only to connect separate areas with each other, but also to confer a unique identity on the immediate environment. Creating a good pedestrian bridge requires a high level of design sensitivity, especially if the bridge is in an inner-city area or a special landscape. Pedestrian bridges are subject to fewer restrictive functional and static demands than road or railway bridges, which gives designers and planners the freedom to respond to specific sites and usages with individual solutions. This book provides an overview of current trends in pedestrian bridge construction. Fundamental static and functional requirements, various support systems, the applications of different materials, and the main economic aspects are all described. The book is rounded off with descriptions of a range of successful new bridges serving to motivate designers and planners to create exciting designs in interdisciplinary cooperation.

- Basic knowledge on all aspects, from design through to support systems
- Explanations of a range of construction principals
- Descriptions of various materials serve as practical inspiration
- Examples of successful projects in urban and natural landscape settings

Author:

Andreas Keil, Dipl.-Ing.

Editorial services:

Steffi Lenzen, Dipl.-Ing. Architect

Cosima Frohnmaier, Dipl.-Ing. Architect

Sandra Leitte, Dipl.-Ing.

Institut für internationale

Architektur-Dokumentation GmbH & Co. KG, Munich