NOVEL CONCRETE BRIDGE DESIGN - AS SIMPLE AS POSSIBLE, BUT NOT SIMPLER

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Dedicated to Prof. György L. Balázs
for his 65th birthday

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The paper discusses the need for a simplified and low-maintenance building culture to address global climate change. A transition to a circular economy, giving priority to efficiency rather than quantity is important. Creating structures with minimum material consumption and minimum maintenance with a maximum of recyclability should be our focus. Integral bridges such as the Duke's Bridge in Germany and the Isarsteg-bridge in Munich are innovatively designed while taking into consideration the soil-structure interaction and the temperature induced stresses in structural detailing. The paper also considers additional technical aspects, such as the calculation of the mobilised earth pressure and the relevant deformations. Finally, a holistic approach that aligns with principles of resource efficiency, simplicity, and sustainability is suggested.

Keywords: Integral bridges, resource-efficient, sustainability, soil-structure-interaction, mobilized earth pressure

1. INTRODUCTION – SOME BASIC IDEAS

It is time to adopt a more simple and recyclable building culture to combat climate change, which knows no borders and is a worldwide reality (Glock, Haist, Bergmeister, Voit, Beyer, Heckmann, Hondl, Hron, Schack, 2023). The building industry must undergo a significant transformation, with all materials and resources integrated into a circular economy. Innovations must prioritize efficiency over quantity in the future. This publication focuses on the beauty of simple, but not simpler structures.

The goal should be to build structures that are as simple in terms of material consumption as possible, and as recyclable without waste as possible, as Einstein (1879 – 1955) once said.

The aim of resource-efficient design, dimensioning and construction is to align the load-bearing structure with the load-bearing force flow while taking aesthetics into account. Only as much material should be used as is absolutely necessary!

In current research, load-bearing structures are often designed as bar structures or arches. Optimization methods are also used to take shapes from nature, such as trees, plants and structures, in order to develop a bionic load-bearing structure. However, real construction is more complex! In addition to the primary load transfer, load-bearing elements are also used for installations and extensions. Therefore, newly designed load-bearing structures should be designed both for a long service life and for the most flexible use possible!

In general, we need to focus on resource-efficient and emission-low design developing structural details which require less maintenance as possible and have a predictable life span. Therefore, integral bridges can be for span lengths up to 80 m one piece of the solutions. There is not one solution in order to face climate change, but we have to promote many solutions and we have to change our mindset.

2. LESS IS MORE – BEAUTY REQUIRE AN EFFICIENT CONCEPTUAL DESIGN

Ludwig Mies van der Rohe (1886-1969), the renowned architect, advocated for resource efficiency through the principle of minimalization, famously known as "less is more," which he incorporated into his designs. Simplicity in design does not necessarily mean designing a simple structure, but rather designing a structure that is efficient and uses the minimum amount of materials necessary for its function. This approach can lead to elegant and beautiful designs that are both sustainable and functional. By minimizing the amount of materials used, we can reduce the environmental impact of construction and ensure that resources are used efficiently. Additionally, a focus on simplicity can lead to designs that are easier to construct and maintain, reducing the overall cost of the project.

Plato (428 - 348 BC), the ancient Greek philosopher, is often credited with the quote "Beauty of style and harmony and grace and good rhythm depend on simplicity." This quote reflects the idea that simplicity in design can lead to beauty and harmony in the built environment. In our times, less is more satisfies points like: zero waste (Natanian, 2020), zero energy, zero, emission, less materials, time-save for the realization, easy functionality and less maintenance and finally an authentic and beautiful architecture. Integral bridges satisfy almost every point and they can be built also for an extended life span over 100 years.

3. INTEGRAL BRIDGES

New research on structural details considering the temperature induced stresses are the basis for novel developments of integral bridges (Tue, Della Pietra, Mayer, 2021). The structure-soil interaction play a very important issue and has to be calculated carefully. The choice and application of soil parameters in the design have a major impact on the overall behaviour of a structure. Two philosophies can therefore be pursued in the design:

- Formation of a low degree of restraint in the area of the abutments or supports and low bending stiffness of the foundation. Due to the flexibility, a certain rotational capability of the superstructure can be assumed and the frame corner can be designed relatively simply due to the lower moments. The field moments are similar to those of a conventional supporting structure. This practice is very common in the USA and Canada and is documented in the associated guidelines (e.g. for sheet pile foundations, even for longer supporting structure lengths and temperature gradients)
- High bending stiffness of the abutment or short, solid supports as well as a massively designed foundation lead to a high clamping effect of the superstructure. As a result, lightweight superstructures can be designed because part of the moment is shifted from the field moment to the frame corner. However, the formation of such a frame corner requires more effort for structural detailing. Furthermore, the desired clamping moment must also be realized for the foundation, which inevitably results in high earth resistances and consequently also possibly high undesirable constraints.

The amount of mobilized earth pressure is determined by the size of the abutment wall displacement. This can be determined in different ways, whereby the translational and rotational components must be taken into account in the calculation. Also a simplified earth pressure (e.g. rectangular or triangular (RVS, 2018)) can be used for the design in order to capture the effects of the mobilised earth pressure .

$$e_{\mathrm{mob}} = e_0 \cdot [1 + \mathrm{L} \cdot (0.06 - 0.005 \cdot H)] \geq e_0$$

e_{mob} = *mobilised earth pressure*
e_o = *earth pressure*
H = *Height* [m] $\leq 10m$
L = *Span length* [m] $\leq 30m$

The cyclical shift due to the temperature change ΔT results in a pumping movement over the service life of the structure. This leads to an increase in earth pressure when the structure extends (mobilised passive earth pressure) and to a reduction in earth pressure compared to the earth pressure, when the structure is shortened (mobilised active earth pressure). The amount of mobilised earth pressure depends on the size of the abutment wall displacement ΔL. A slight movement away from the soil is sufficient (-ΔL ≈ 0.05% - H) to mobilise the active earth pressure eactive. On the other hand, large displacements (+ΔL ≈ 5% - H) are required to fully mobilise the passive earth pressure. However, the necessary large displacements do not occur in the integral bridge construction, resulting in only a partial mobilisation of the passive earth pressure e_{mob} (Della Pietra, 2017).

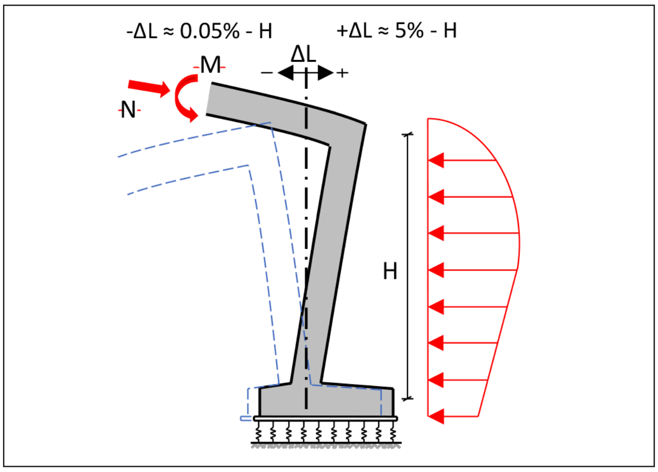


Fig. 1: Schematic force flow of the earth pressure in the abutment zone (taken from Ref. Della Pietra, 2017)

The following calculation options can in principle be adopted:

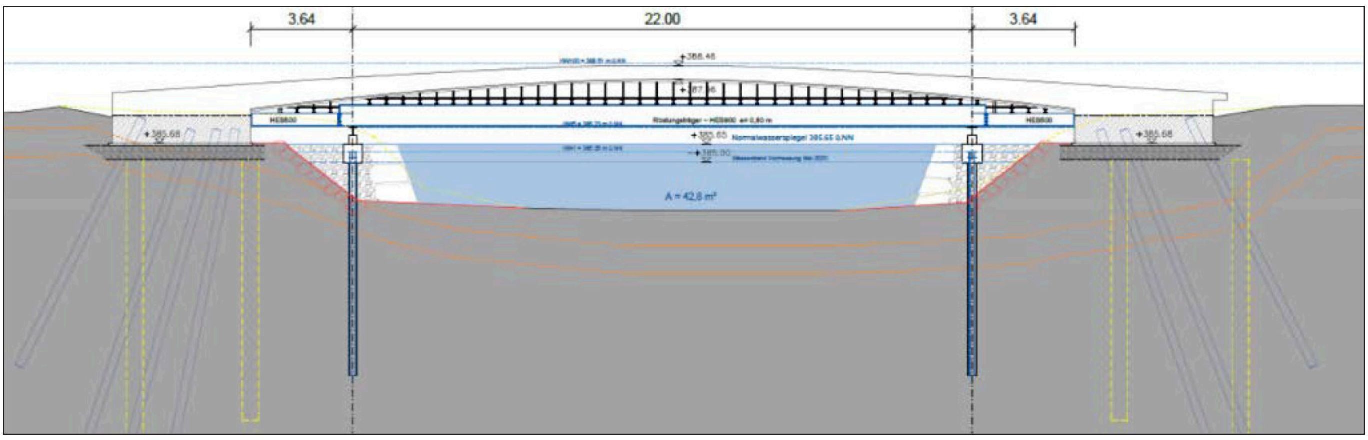
- iterative determination of the abutment wall displacement on a model, taking into account a damping factor
- direct determination of the abutment wall deformation on a model, taking into account the existing structural and foundation stiffnesses
- measured values on similar integral bridges.

3.1 An integral concrete bridge

The new Duke's Bridge in Eichstätt - Germany, which was awarded the Bavarian Engineering Award in 2023, is a prime example of beauty, simplicity, and resource efficiency (Bergmeister, Taferner, 2023). The goal was to create a simple monolithic structure with low-maintenance, and without any waterproofing or surfacing layers.

The bridge is a cantilevered integral design with no

Fig. 2: Longitudinal section of the integral Duke's Bridge (www.bergmeister.eu)



bearings or joints over a length of approximately 30 m. The frame effect is activated by cleverly arranged small bored piles under the strongly designed abutments. The counterweight of the abutments and pairs of forces from the pile foundation transfer the restraining moments. The load-bearing capacity is enhanced by the passive earth pressure. The mobilized earth pressure was determined by wall displacement under summer temperature conditions. In Germany only the summer case is taken into account for the calculation of the mobilised earth pressure, wherever in Switzerland and Austria the total deformation (summer and winter) is used to take. The abutments of the Duke's Bridge are fully integrated into the embankment, and the forces are transferred into deeper load-bearing gravel through small, slightly inclined, grouted bored piles with a diameter of 78 mm.

The integral bridge was designed with an asymmetrical waisted shape. Its structure consists of a flatly curved bending beam made of reinforced concrete that is clamped at the abutments, with a maximum longitudinal inclination of the carriageway of 6%.

The bridge's design widens in a trumpet-like direction, resulting in a width of 5.5 m on one side and 9.8 m on the other. The maximum slab thickness close to the abutment is 90 cm, while it is 50 cm at the apex. The cross-section of the bridge is streamlined to the edges, similar to a profile suitable for flood discharge. The rounded underside of the bridge is designed to minimize the surface area for floodwater, flotsam, and debris while offering deflection possibilities in the direction of flow. In the event of a flood, the railing can be easily dismantled by hand within a very short time.

Fig. 3: Overview of the integral Duke's Bridge (www.bergmeister.eu); completed in 2022; "Prize of Bavarian structural engineering 2022", Architectural Design: J2M Mayr Metz Architekten, Munich; Structural Engineering: Bergmeister Ingenieure GmbH

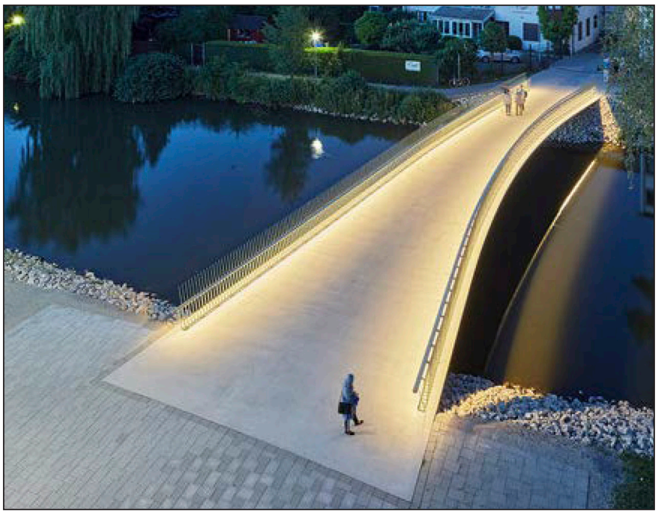


Fig. 4: Overview of the integral Duke's Bridge (www.bergmeister.eu)

To analyze various deformations, specific 3D calculations were conducted considering shrinkage and long-term creep effects. Additionally, dynamic investigations were carried out to assess possible vibrations, resulting in a first eigenmode in the form of a vertical sinusoidal movement with a natural frequency of 2.57 Hz and a modal mass of approximately 65 tons.

In terms of durability, the carriageway slab was coated with double-deep hydrophobic layers to ensure a minimum lifespan of 100 years even under severe environmental conditions or flooding events. A probabilistic calculation for the durability (***fib*** Bulletin 76, 2015) was carried out for a service life of 100 years. An average concrete cover of 42 mm with a standard deviation of 9 mm was selected. The required reliability index β at the end of the estimated service life of 100 years was assumed to be $\beta = 0.5$ for an exposure class XD3. In any case, it was assumed that the bridge is regularly

Fig. 5: Overview of the integral Corten-steel Isarsteg-bridge (www.bergmeister.eu) completed in 2015; "Prize of German steel construction" 2016, Architectural Design: J2M Architekten / Ch. Mayr, Munich; Structural Engineering: Bergmeister GmbH & structures, Photo: O. Jaist

inspected and maintained.

Additionally, specific laboratory tests were conducted on the casted concrete to verify the chloride migration coefficient. The proportion of granulated blast furnace slag in the binder was increased to reduce hydration heat and improve post-hardening and chloride penetration resistance. Stainless steel reinforcement of grade B500B NR/B670B NR "Top12" (material no. 1.4003) was utilized.

3.2 An integral steel bridge

The Isarsteg-bridge in Freising near Munich is an integral steel bridge made of Corten steel. The entire load-bearing structure is composed by the slender superstructure, the stairways and ramps and the soil. All components are connected in a monolithic manner and designed without sliding bearings and joints. The 58 m long river crossing has a triangular, torsional rigid, airtight and watertight welded steel box girder with a variable cross-section.

There are transverse bulkheads every 3 meters inside the box girder. The composite structure consists of the cover plate of the box girder and a 15 cm thick reinforced in-situ concrete slab.

The superstructure from the lower edge of the girder to the upper edge of the pavement, has a constant height of 1.20 meters over the entire length. Its structural height is primarily based on two aspects:

1. The lower edge corresponds to the specified freeboard (distance between the water level and the lower edge of the footbridge), which protects the bridge from damage caused by floating debris in the event of flooding.
2. The walkway level was not allowed to be too high above the embankment paths so that the gradient of the ramps would not be too steep for wheelchair users.

The structurally favorable triangular shape and the ability to respond to different force and moment curves with different sheet thicknesses and cross-sectional shapes also creates a lightweight, robust and economical supporting structure. The clear lines of the bridge required the cantilevering of the hollow box girder, which deforms by around 72 mm (approx. l/780) under maximum live load (traffic).

The first natural vibration frequency of the structure is 1.33 Hz with a modal mass of 65 tons. A vibration damper in the box girder under the pavement slab ensures user comfort.

The novel design and integrative construction method support the sensitive embedding of the structure in the floodplain landscape, which has been designated as particularly worthy of protection. They also contribute to the fact that the bridge can be described as extremely sustainable without any sliding bearings and expansion joints, which are often made of environmentally harmful materials and are also maintenance-intensive.

Finally, the bridge consists of only two materials:

1. reinforced concrete for the pavement slab and foundations and
2. weldable, weather-resistant structural steel S355 J2G2W (steel in accordance with EN10155 or EN10025-5) for the entire steel structure.

The Corten steel does not require any additional corrosion protection due to its dense oxidized rust coating. In addition, the red-brown color integrates in the landscape as a "branch or tree trunk exposed to the forces of nature". The whole bridge is barely visible from a distance, it emphasizes the lightness and elegance of a bridge structure that sees itself as part of a unique natural landscape.

4. REMARKS ON INTEGRITY AND CONGRATULATIONS TO PROF. GYÖRGY L. BALÁZS

Integral bridges and integral personalities have a lot in common. Integral bridges have a distinguished and humble appearance, are acting together with the soil and require almost no maintenance. György L. Balázs is an example of an integral personality. He always creates an environment of

Fig. 6: *Isarsteg-bridge integrated within the natural landscape (www.bergmeister.eu)*

integrity and humility. As Nelson Mandela said:

„You can never have an impact on society if you have not changed yourself. Great peacemakers are all people of integrity, of honesty, but humility."

Prof. Balázs has a worldwide impact in civil engineering science and on society. I would like to thank him warmly for his outstanding engagement and for our long friendship.

Ad multos annos!

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