Dimensioning Concept for Integral Composite Bridges with Sheet-Pile Abutments

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Abstract Integral composite bridges with sheet-pile abutments represent a modern approach to bridge construction, combining the benefits of appropriate material choice (steel in tension and concrete in compression) and integral bridge design. This method eliminates the need for conventional expansion joints and bearings, this reducing the maintenance requirements and enhancing structural integrity. Especially for medium spans up to 45 m, the use of prefabricated elements such as VFT®-girders, helps to increase the economic feasibility as well as construction speed. Using sheet-piles as permanent foundation elements allows for greatly reduced carbon emissions and excellent soil retention capabilities near waterways, where sheet-piles are commonly used as pit-protection systems during construction.

For a widespread application of integral bridges with sheet-piling abutments, a generalized approach to dimensioning is currently lacking, preventing engineering acceptance. Within the scope of FOSTA research project P1521 “Integrale Spundwandwiderlager von modularen Verbundbrücken für einen zeiteffizienten Bauablauf” various investigations on the load bearing behavior of a modular frame corner in composite construction have been performed to identify load paths and capacities of different elements used.

Based on these investigations, the following paper proposes a simple dimensioning concept for spans up to 45 m using mostly modular construction while considering all relevant loads and structural effects from temperature and soil-structure interaction. The assumptions of the concept are cross-checked by numerical calculations using detailed FE-simulations to confirm load paths and section utilization.

1 Bridge infrastructure in Germany

With a total length of 830,000 km, the German road traffic network is Europe's second largest after France (1.02 Mio. km) [1]. With a GDP of roughly 3.7 trillion Euros, it is by far Europe's economically strongest country. Located adjacent to many of Europe's other economically important nations, like France, the Netherlands and the United Kingdom, its roads play a major importance in the performance of the entirety of the European trade and economy. Part of this road network are roughly 120,000 bridges [2], 40,000 of which are part of the federal highways [3]. These bridges and their structural health can greatly impact the overall quality of the network in a negative way, which is why maintenance and replacement of ageing bridges is one of the key tasks of the federal ministry of transportation.

Of these 40,000 bridges, roughly two thirds (68.7%) are constructed in prestressed concrete construction, see **Figure 1**. Another 17.2% are reinforced concrete, totaling to 85%. Composite bridges amount to 7.1% and steel bridges 6.4%. Neglectable amounts are built in masonry or timber construction. While the share of composite bridges is significantly lower than those made of majority concrete, the share has shifted in the past, with more composite bridges being built [4]. The main advantage of composite bridges compared to those in concrete is the advantageous usage of steel and concrete according to their material properties. While steel offers high tensile strengths with slender cross-sections, concrete decks allow for cheap compression strength near the neutral axis of cross-sections. Composite bridges therefore offer the possibilities of slender beams and large spans without the need for additional piers.

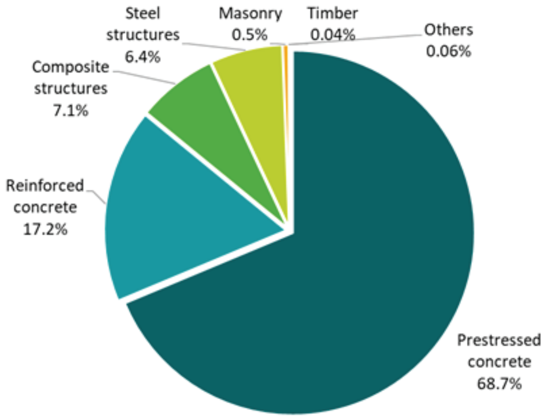

Figure 1: Federal bridges by material [3]

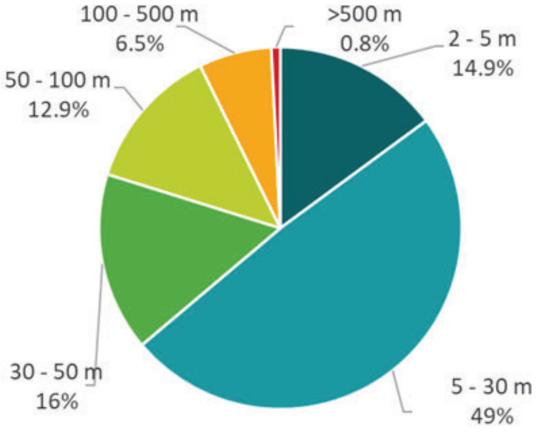

Figure 2: Federal bridges by length [3]

A majority of the bridges in Germany's road network have been built during the post-war economic rise between 1960 and 1980 [3; 4]. As such, these bridges are approaching the end of their intended life-time, while many already suffer from degradation and structural defects. This can be shown by the condition grading derived from structural data collected during regular assessments according to DIN 1076 [5; 6]. These condition grades evaluate the structural health of a bridge according to categories like structural safety, road safety and durability. Grades range between 1.0 for excellent condition and 4.0 for inadequate condition.

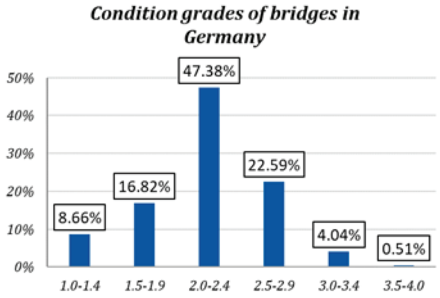

Figure 3: Condition grades of bridges in Germany [5]

According to Germanys road authority, bridges with a condition grade of 3.0 and worse require maintenance work in the near future, while bridges with a condition grade worse than 3.5 are threatened by closures. Bridges with a condition grade between 2.5 and 2.9 are commonly showing signs of degradation, meaning that maintenance work in the medium-term future should be taken, to prevent these bridges from degrading further. According to **Figure 3**, 4.5% of all bridges already suffer from serious deficiencies, while a further 22.6% are in condition grades 2.5 - 2.9. With such a substantial amount of infrastructure needing maintenance or replacement work done, special importance lies on the use of sustainable design concepts. Whereas in the past, the main criteria in the choice of different designs were mostly construction costs, new findings prove a significant effect of life-cycle and economic costs due to disturbances of traffic. As such, proposed designs should not solely focus on being cheap to construct, but should also consider costs accumulated over the lifetime of a bridge, as well as external costs.

One proposed design featuring all of these aspects are integral bridges. Due to their lack of bearings and transition joints, maintenance requirements are kept to a minimum. In conventional bridges, a majority of life-cycle costs comes from regular required inspection and maintenance of these vital parts, which in many cases also requires road closures during work shifts. Due to the restraint of main beams in the abutments, integral bridges also allow for longer spans without the need for intermediate piers. This increases construction speed while also preserving flexibility of the traffic below the structure. This advantage however is also the biggest challenge of integral bridges. Due to the monolithic combination of superstructure and substructure, temperature effects of the deck have to be taken directly by the soil creating internal stresses. This is called soil-structure interaction and combined with a lack of experience from engineering offices and construction companies currently prevents integral bridges from widespread application.

In order to facilitate the sustainable use of materials and design systems, the research project “Integrale Spundwandwiderlager von modularen Verbundbrücken für einen zeiteffizienten Bauablauf” was funded by German Steel Research Association FOSTA. The scope of the project aims to propose a dimensioning concept for an integral frame bridge in composite construction, using modular elements like VFT®-girders and combined sheet-pile abutments for rapid construction. As part of the research, numerical and experimental tests are performed on different parts of a proposed connection to analyze load paths and utilizations of elements. Based on these findings, a dimensioning concept is proposed for practitioners.

2 Investigations of a modular frame corner

Figure 4 shows a scheme of the proposed frame corner node. The setup shown corresponds to numerical and experimental tests within the scope of the project, where prefabricated elements have not been displayed. The frame corner node incorporates the main beam, a composite girder, and the king steel profile from the combined sheet pile wall. The negative bending moment transfer, from the main beam to the combined wall, is mainly achieved into the node by a pair of forces in vertical direction as well as the surrounding peripheral reinforcement. Compression forces are transferred through a compression profile between the main beam and the king-pile of the combined wall. As per the project's scope, this detail follows the principal of modularity of the connection. On-site, the combined wall is rammed into the soil. As soon as the final position is reached, the top part can be oxy-cut. As the cut edge will be uneven, the compression profile is placed on a supporting console "steel chair" bolted to the king-pile. This allows for easy compensation of on-site tolerances together with fast construction progress.

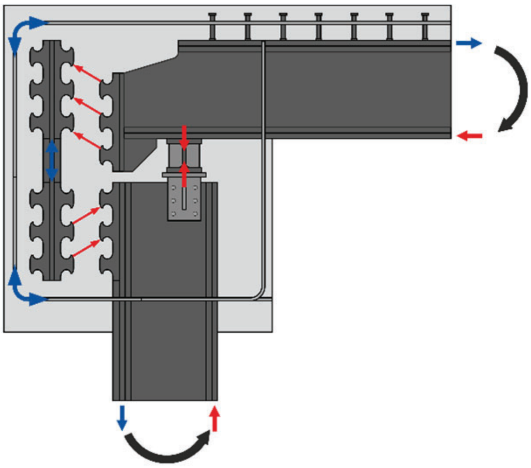

Figure 4: Proposed connection with schematic load paths

The tension force at the frame corner is partially transferred through a shear joint in the back of the node. This allows for an exchange of forces without the need to establish direct contact between the main beam and the king-pile profiles. Shear forces are introduced into a steel strip in the back of the node via composite dowels on the main beam and the steel plate. In the steel plate, these shear forces act as tension forces and are subsequently transferred to the king-piles via another set of composite dowels. This way, the king pile takes a bending moment from the compression forces in the front of the king-piles and a tension force from the steel teeth in the back, leading to the support reaction. Since the steel plate is located in the joint between the prefabricated element and the in-situ concrete, additional composite dowels are also welded to the back-side of the plate to provide for anchorage in the prefabricated element. Another part of the tensile force is transferred through a corner reinforcement commonly found in conventional frame bridges. The reinforcement can be greatly reduced due to the forces taken by the shear joint.

Within the project, tests have been performed on different parts of the connection, showing failure modes and load paths within the nodes. Results from early stage small-scale tests showed significant pry-out of the upper concrete cover due to a punching shear of the top-most steel tooth of the main beam. In the experimental tests, it was observed, that from the three dowels used, the top one received the smallest amount of deformation (Figure**Figure 5**). This is due to the lack of a direct counterpart at a skewed angle, which is confirmed by numerical modelling as shown in **Figure 6**. As a consequence, the dowels of the main beam are shifted down to allow for a direct force transfer to opposing dowels in an angle of roughly 45°. The numerical models of **Figure 6** and **Figure 11** are calculated using ABAQUS/CAE with volumetric modelling. All steel components are cut from the concrete, with frictional contact (μ=0.3) between interfaces and hard contact. All reinforcement is modelled volumetric as well and encased in the concrete using the "embedded region" function of ABAQUS. The concrete material was modelled with the *Concrete Damaged Plasticity* model to account for degradation in both tension and compression, with material strengths taken from sample tests.

Figure 5: Deformation of steel teeth in static test of upper part

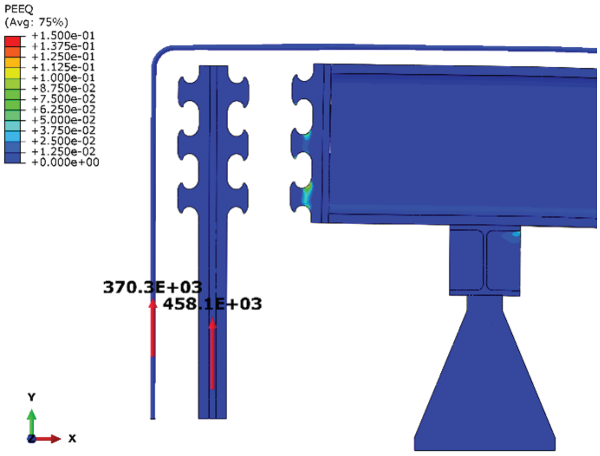

Figure 6: Plastic strain of steel teeth as calculated in numerical model

3 Dimensioning concept of the integral frame corner

3.1 General Assumptions

Based on the experimental tests and numerical simulations performed on various parts of the connection, a dimensioning concept is proposed to allow for the application of the findings. This dimensioning concept is based on several principal assumptions, aiming to guarantee a realistic and practical solution.

The main objective is for the concept to be simple to use. As stated before, integral composite bridges still suffer from reluctance in engineering practice, due to limited experience from both engineering offices and construction companies. To overcome these reservations, the concept needs to be intuitively easy to apply, with clear advantages over conventional approaches. To achieve this, a simple and safe-sided verification procedure of the individual elements is proposed rather than a detailed, more accurate verification representing the “exact” stress-strain state. While the latter might lead to higher economic advantages, it also requires engineering offices with the background and willingness to adopt entirely new concepts.

Being a steel and concrete composite construction, the verifications shall be based on the relevant Eurocodes EN 1992, EN 1993 and EN 1994, as well as available documents for the dimensioning of the elements used like DIBt approvals. Also, adjacent industry standards like RE-ING and ZTV-ING will be followed.

Elements of uncertain degree of contribution, like natural bond between concrete and steel-profile surfaces and tensile strength of the concrete are ignored to further simplify the concept. This introduces additional safety margins between the verification and actual performance of the frame corner.

During construction, the VFT®-girder is placed on the supporting console “steel chair” with the compression profile. The system at this stage is considered simply supported with no bending moments transferred between superstructure and sheet-piles (stage 1). Once the precast elements are in place and the node is reinforced, the in-situ concrete is poured, creating a monolithic connection between elements (stage 2). Depending on the concreting stages (i.e. starting with mid-span vs. starting with frame corners) different restraining moments can be achieved. The dimensioning of the frame corner is shown by assuming the most critical setup.

As only shear forces are transferred in the construction stage, the dimensioning at this point is greatly simplified. Verifications are limited to the compression support of the main beam consisting of the compression profile itself as well as the bolted connection of the “steel chair” in shear. Normal forces and bending moments are not transferred at this point.

In the second stage, the connection is designed to transfer any additional vertical forces (additional loads, traffic loads) as well as the bending moments resulting from these loads. Normal forces from temperature effects on the structure are also transferred. Distinctions need to be made between summer and winter case as the superstructure extends and contracts. These normal forces are transferred by the main beams’ friction in the node. The verification in this case follows EC2 guidelines, without any of the remaining elements being used for normal force transfer. Inside the node, the normal forces are transferred to the king-piles by a shear force acting in bearing pressure on either side of the king-pile activated by the corresponding beam deformation.

The shear force is once again only taken by the compression profile, as this steel-to-steel connection possesses a higher stiffness than the surrounding concrete. Verifications for stage 2 therefore are the same as for construction stage, with added loads from load models including traffic loads.

The bending moments verification is done according to the schematics of **Figure 7** and **Figure 8**. The impacting bending moment is split between a set of forces transferred through the composite joint and the compression profile, and a second set of forces transferred through the peripheral reinforcement.

Based on the calculated forces, cross-sections of the composite dowels and the required reinforcement are determined.

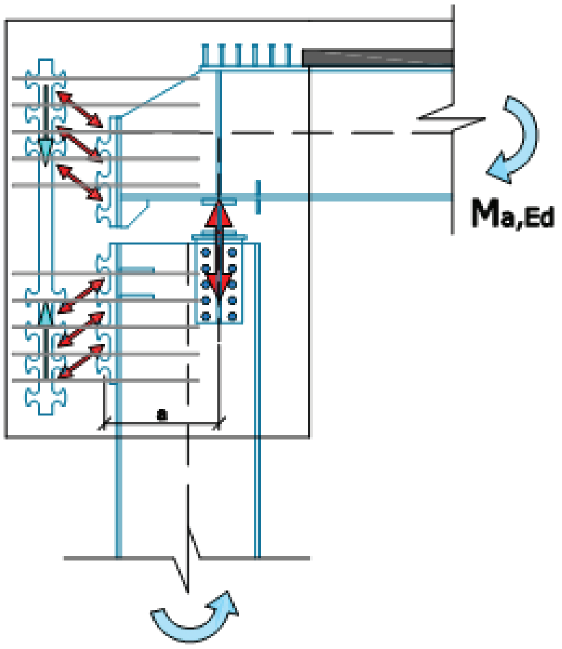

Figure 7: Bending moment transfer through shear joint

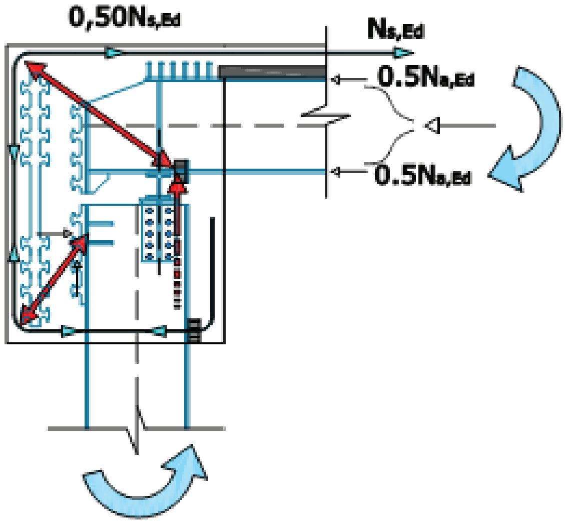

Figure 8: Bending moment transfer through peripheral reinforcement

3.2 System description and loading

The proposed concept is aimed at designs with spans of up to 45 m. As shown before, this covers a large majority of all bridges in Germany's federal road systems and even more bridges in communal liability. For a sample calculation, a typical cross-section of 12 m width consisting of six main beams HL 1100B in S460 with a spacing of 1.927 m was chosen. For the bridge deck and the corner node, a concrete grade C45/55 is assumed. In order to determine the relevant internal forces introduced into the frame corner, the loads considered include: self-weight and permanent loads, traffic loads according to load models LM1 and LM4 of EN 1991, acceleration and braking forces, support settlements and temperature loads due to contraction and expansion of the bridge. Combined with these temperature loads is also the soil reaction, being considered in the form of active and mobilized passive earth pressure. Not considered are accidental and seismic loads.

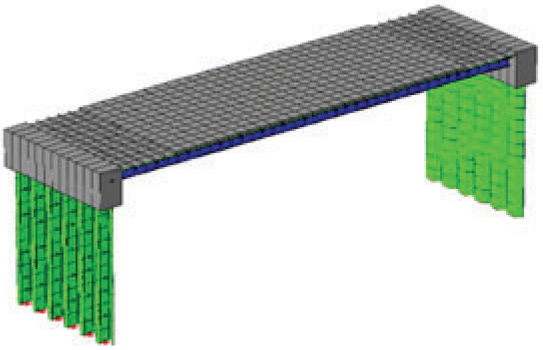

Figure 9: Numerical model of sample bridge with sheet-pile abutments

A model of the bridge according to RE-ING part 2 section 5 is created in InfoCAD, split between the construction stages. The model for the final stage is shown in **Figure 9**, with cracked concrete cross-sections being assumed for the sections of negative bending moments.
The soil reaction in this model is achieved by using spring elements in horizontal direction with spring stiffnesses assigned depending on the depth and the soil's reaction. The spring stiffnesses are taken according to RE-ING with active and mobilized passive earth pressure.
This model is subsequently used to calculate internal forces at the concrete face, where the beam enters the node.

3.3 Sample calculation

In order to demonstrate the dimensioning concept, the verification is shown for the sample bridge described in point 3.2. The calculation is performed for an isolated beam section of the entire set of beams. All forces are taken at the concrete face, as described before. **Figure 10** shows the internal forces of the node resulting from the bending moment of 3900 kNm and the shear force from stage 1 and 2 equating 850 kN. These load transfer paths are also cross-checked with numerical simulations of the frame corner, shown in **Figure 11**. The model displayed utilizes symmetry constraints, so all forces have to be doubled to be compared to the forces determined analytically.
As shown in **Figure 10**, the impacting bending moment is split into tension and compression shares distributed between the steel profile and the tension reinforcement. The tensile force of 1250 kN in the reinforcement is taken by 12 diameter 25 bars per girder. The force components of the profile are split into a compression part transferred to the king-pile via a compression profile. This force is calculated to be 2500 kN, being taken by a HEM 240 profile in S355 or higher. The bolted connection of the "steel chair" has to transfer this load via shear and bearing pressure. In this case, 10 M36 10.9 bolts are used, providing a total capacity of 4730 kN.

The tension force of the profile is transferred through the shear joint into the steel strip. For this calculation, the formulae according to the composite dowels' technical approval are used:

$$\begin{aligned} P_{pl,k} &= 0,25 \cdot e_x \cdot t_w \cdot f_y \\ P_{sh,k} &= \eta_D \cdot e_x^2 \cdot \sqrt{f_{ck}} \cdot (1 + \rho_D) \end{aligned} \tag{1}$$

The failure mode "pry-out of a concrete cone" is neglected, as this mode only applies to composite dowels in concrete plates of beams. In the present case, pry-out cones are prevented by significant concrete cover as well as opposing composite dowels, counteracting the pry-out forces. For the chosen dimensions of $e_x = 250\ mm$, $t_w = 20\ mm$ and $e_y = 200\ mm$, failure of the steel teeth becomes the governing failure mode with a design capacity of 355 kN per dowel. The staggered arrangement of composite dowels between the beams and the steel strip prevents a punching failure while guaranteeing optimal load transfer between elements. As the lower composite dowels receive forces from the steel strip as well as deviation forces from the reinforcement, the thickness of the steel teeth is raised to $t_w = 25\ mm$.

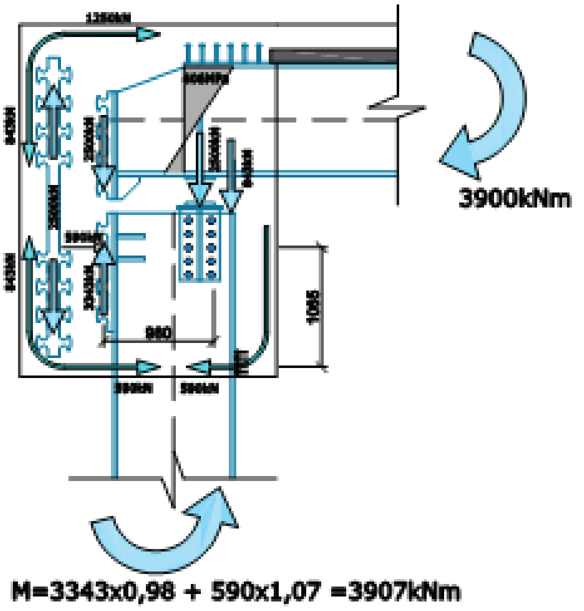

Figure 10: Internal forces calculated from combined shear force and bending moment

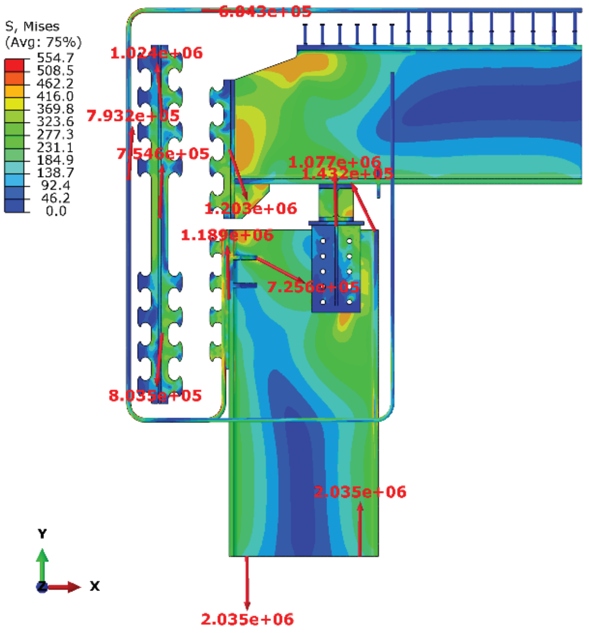

Figure 11: Load paths as calculated from numerical model

The vertical component of the compression struts in the composite joints are taken by their counterparts on the steel strip. The horizontal projection has to be taken by surrounding reinforcement in the node, provided by diameter 20 bars each side of the connection. The reinforcement of the shear joint between the composite dowels is taken according to the technical approval and therefore not part of the detailed calculation of the concept. As **Figure 12** shows, the setup of the composite joint is simply mirrored, with transversal bars running between the steel teeth on both sides.

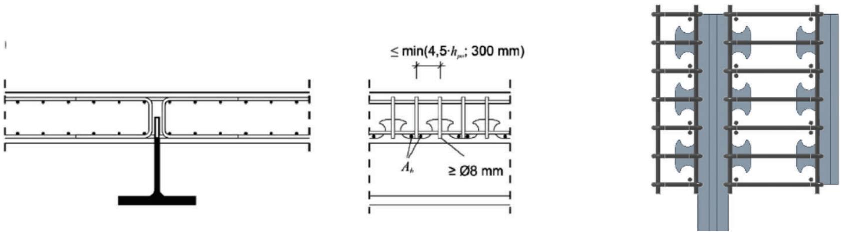

Figure 12: Reinforcement as required in the technical approval (left) and used in the concept (right)

4 Conclusion

In this paper, the current situation of bridge infrastructure in Germany was shown and connected to the economic performance of Germany and neighboring countries. Due to their age and increased traffic, especially heavy traffic, bridges commonly show degradation ranging between increased maintenance costs up to full closures. These restrictions lead to high economic losses due to traffic jams and overloading of diversion routes.

Integral composite bridges offer the possibility to cover a large majority of span lengths in the infrastructure network, without the need of additional piers. Due to the constraint at the abutments, field moments can be reduced with more slender cross-sections being viable. Combined with the use of modular elements and sheet-pile foundations, this design offers advantages in life-cycle and economic costs with increased construction speed.

As experiences from engineering offices are limited, the research project P1521 proposes a simple and safe-sided dimensioning procedure for these types of bridges. General assumptions of the concept are shown with example calculations for a bridge spanning 40 m.

The forces obtained from an engineering model are applied for the concept, with verification being shown for most relevant parts of the connection. A comparison to detailed numerical models shows generally matching forces in the elements, confirming the assumed load paths.

The proposed concept can be used by engineering offices and practitioners alike to replace ageing bridge infrastructure, securing the performance of Germany’s road traffic network.

5 Acknowledgment

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