Design Study of Two Variants of a Pedestrian and Cyclist Bridge in Timber-Composite Design as a Construction Replacement Option for the City of Koblenz

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1. Introduction

Timber-composite constructions are increasingly gaining ground in building construction and structural engineering due to their efficiency. This is demonstrated by several realized projects in building construction such as the "LCT One" in Bregenz and the multi-family house "e3" in Berlin. There are also several timber-concrete composite bridges such as the "Schiffarth bridge" in Rhein-Sieg district, two timber-concrete composite bridges in Schwäbisch-Gmünd, and the timber-concrete composite bridge in Winschoten. In the backdrop, the possibility of a replacement construction for a pedestrian and cyclist bridge in a timber-composite design is investigated in a real project by testing the feasibility of substituting concrete by granite. Using concrete as a load-bearing top layer demands a protective layer which has to be replaced regularly. This leads to high maintenance costs for the developer. Furthermore, the renewal of sealing level and road surface has a negative effect on the ecological life cycle balance. Using granite as load-bearing top layer intends to preserve the advantages of timber-concrete composite (TCC) structure and to reduce its disadvantages. Timber-concrete composite structures are generally superior to comparable solid or steel structures in terms of resource-efficient use of building materials. The timber-granite composite (TGC) offers even further optimization potential in this area. The inclusion of holistic considerations about lifespan is a firmly established procedure in building construction [1], which in future will also be applied within the field of infrastructure design. The exclusive consideration of the construction costs of engineering structures ignores their high maintenance costs. These leads to high costs for the developers over the service life.

However, using granite as a top layer is associated with various challenges. The granite slabs are fabricated in limited dimensions and need to be connected separately with timber beam. Depending on the type of fastening chosen for the slabs, the bond between the two construction materials granite and timber may be interrupted. This needs to be taken into account while calculating the internal forces and deformation by using an appropriate calculation method. Furthermore, for the durability of the overall construction the slab joints are to be designed in such a manner that water penetration can be ruled out.

2. Design and life cycle consideration

2.1. Structural design

The existing bridge (Fig. 1) which has to be replaced was constructed in 1970 as an elastic reinforced concrete frame clamped into the subsoil. Its free span is 27.5 metres with 2.40 meters as pavement width. It was required to integrate the existing abutments and previously developed structures into the new design, so the lines of the upper edge of the existing bridge had to be maintained.

Within these given basic conditions, various superstructure variants were designed and pre-dimensioned. The designs take into consideration that the superstructure is suitable for a timber-concrete composite construction as well as for a timber-granite composite construction. Therefore, the comparability of the two variants is achieved.

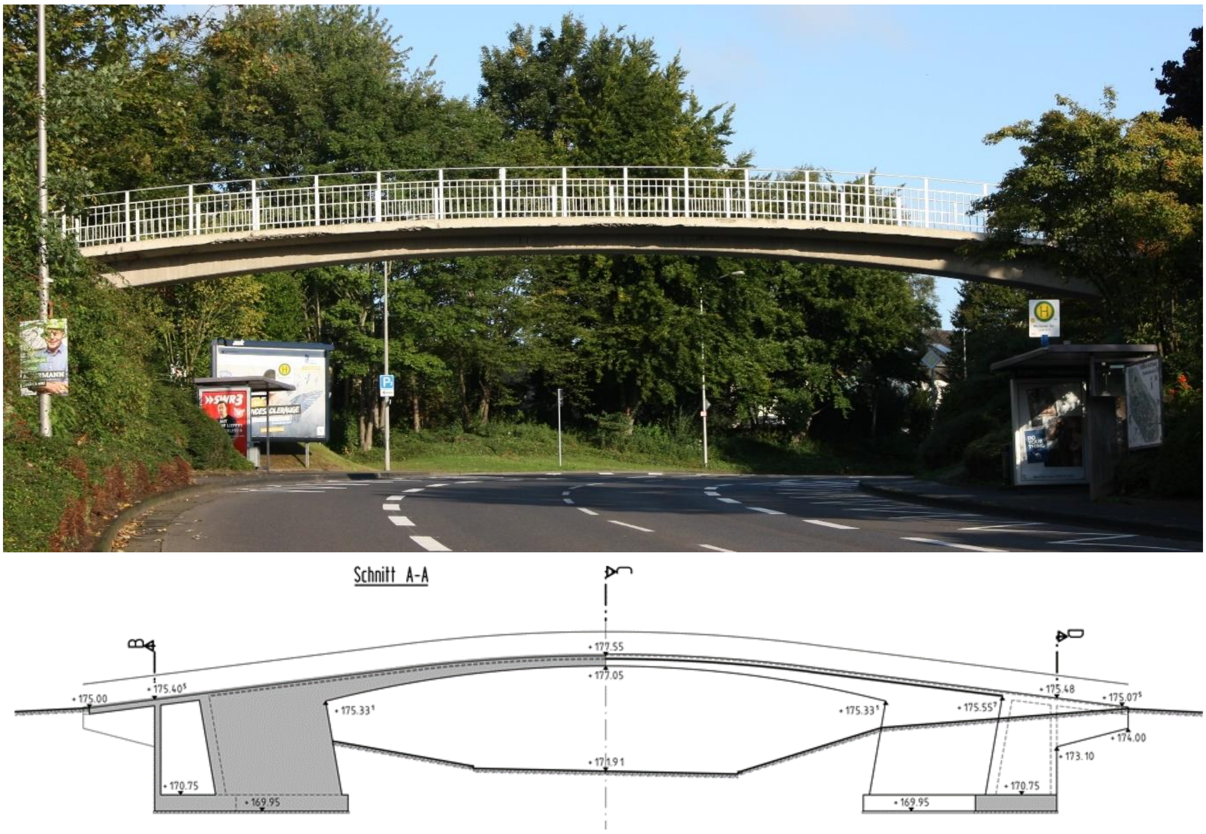

Figure 1: Existing concrete bridge across the Berliner Ring in Koblenz

As tensile forces induced into the planned composite walkway the tied arched bridge (Fig. 2a) was ruled out. Because the mineral top layer should always be under compressive stress. The large number of required joints could also have a negative effect on the durability of the overall structure. From a similar point of view, the variant with a perforated floor (Fig. 2b) was ruled out. These two variants were also rejected due to aesthetic considerations, especially as an arch at the top would not have fitted well into the surrounding area. The variants with a supporting structure of struts attached under the main girder (Fig. 2c), or as an arch (Fig. 2d) cause a continuous girder effect which is accompanied by negative moments in the main girder.

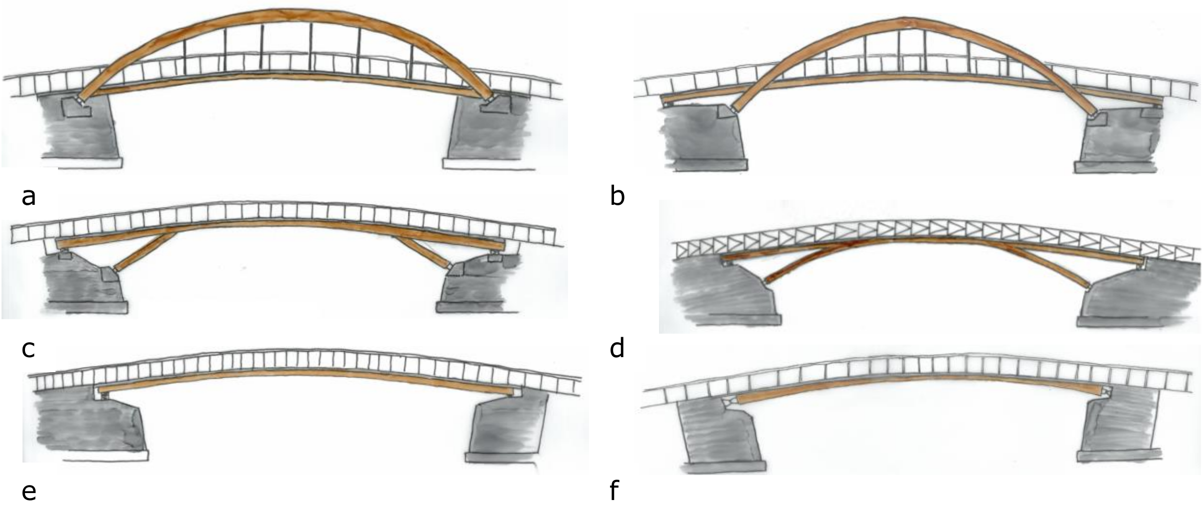

Figure 2: Different variants of the bridge design

These negative moments, in turn, lead to bending stress at certain points on the upper side of the mineral top layer that should be avoided. Furthermore, the position of the struts or arches is severely restricted by the clearance profile of the road which passes underneath the bridge so that an effective reduction of the span is not possible.

A beam-bridge design (Fig. 2e) would have required very high cross sections in order to comply with the deflection restrictions. The necessary cross sections for the beam bridge would have violated the boundary conditions of the design. Thus, the choice fell on a very flat arch construction as superstructure (Fig. 2f). Another advantage of the arched bridge is that additional compressive forces are activated by the arch from its dead load to ensure that the mineral top layer remains under compressive stress.

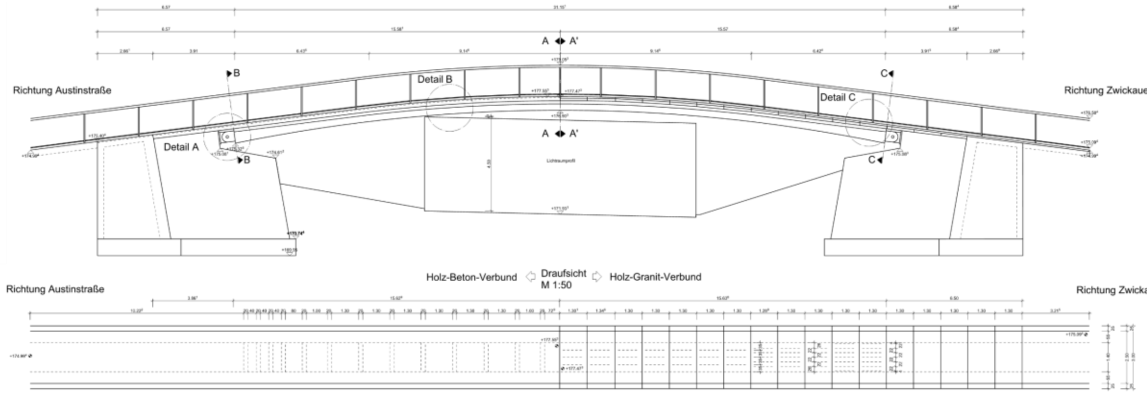

Figure 3: selected arch bridge design

For the chosen bridge's cross section, a bottom chord made of glued laminated timber was selected for both the timber-concrete and the timber-granite variant. Compared to concrete C30/37, which was used for the timber-concrete composite variant, the used granite has not only a higher strength but also a higher modulus of elasticity. Therefore, in the timber-granite variant the height of the top chord can be lower than in the timber-concrete variant, but without worsening the static properties of the overall structure.

For the timber-concrete composite construction, notched connection with a staggered arrangement over length were chosen as connectors. For the timber-granite construction, expanded metal sheets glued into the timber and granite were used as fasteners. The number of fasteners were also staggered over the length according to the static requirements.

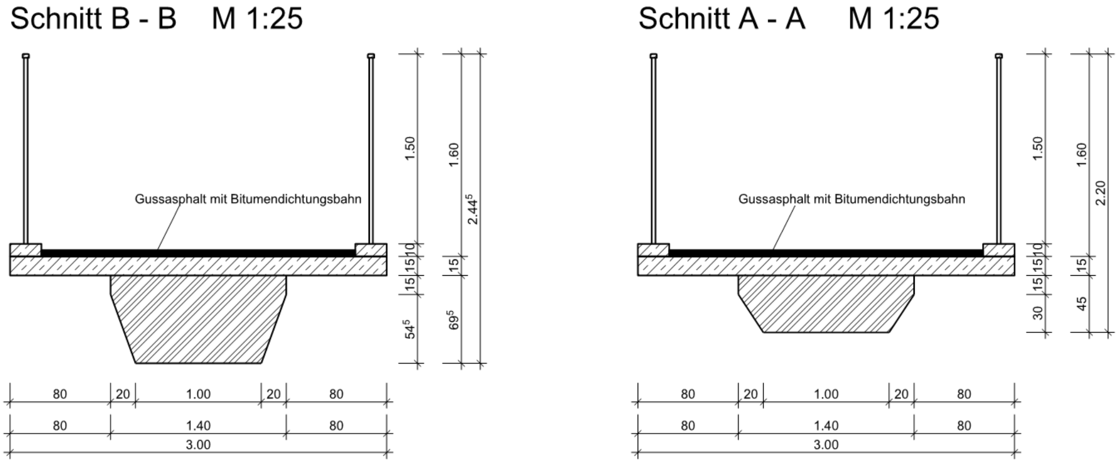

Figure 4: Cross section of the timber concrete composite bridge

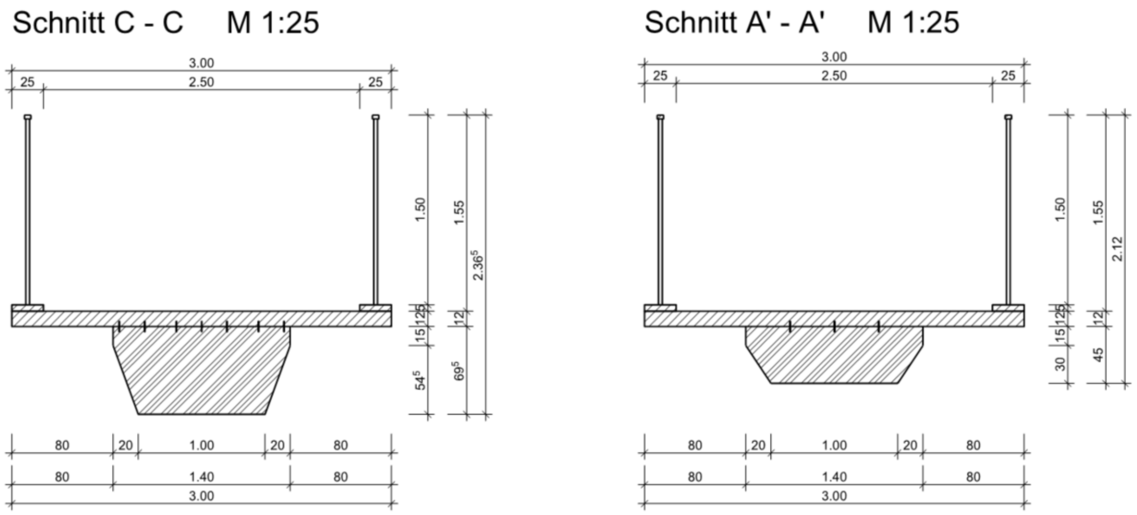

Figure 5: Cross section of the timber granite composite bridge

2.2. Life cycle consideration

The life cycle analysis for both variants is based on the assumption of a period of service of 80 years [2]. The main tasks consist of evaluating the economical as well as ecological costs of the structure holistically over the intended service life. A positive side effect of this consideration is that the running costs can be minimised during the service life. The reduction of usage cost through low maintenance and operating costs plays a major role as they can easily amount to twice the construction costs [3].

The estimated costs of both variants were comparable and move in the context of around 2400 €/m². The economic analysis assumes that the costs for the renewal of the bridge equipment as well as the tests are identical for both variants. However, for the timber-concrete composite variant, a 1.5 times renewal of surface layer and waterproofing is necessary over the service life of 80 years [4]. Considering this, the timber-concrete composite variant has higher maintenance costs as the timber-granite composite variant.

For the ecological life cycle analysis, characteristic values are determined for the different service phases construction, operation, and demolition in order to be able to determine effects of the building on the environment. Based on the existing environmental product declarations, the two variants were compared only with regard to the construction and maintenance phases. For both variants a contribution to the storage of CO_2 could be proven due to the usage of timber and it turned out that both variants have similar environmental effects. Here, the timber-concrete composite variant performed slightly better during construction in the fields of energy consumption (PERT and PERTN) and Global Warming Potential (GWP) since a lot of energy is required for the mining, manufacturing, and transporting the slabs. If, however, the renewal of the roadway and the waterproofing over the service life is considered, the timber concrete composite variant loses a large part of the potential CO_2 storage. Furthermore, the consumption of non-renewable energy (PERTN) increases drastically (Fig. 6).

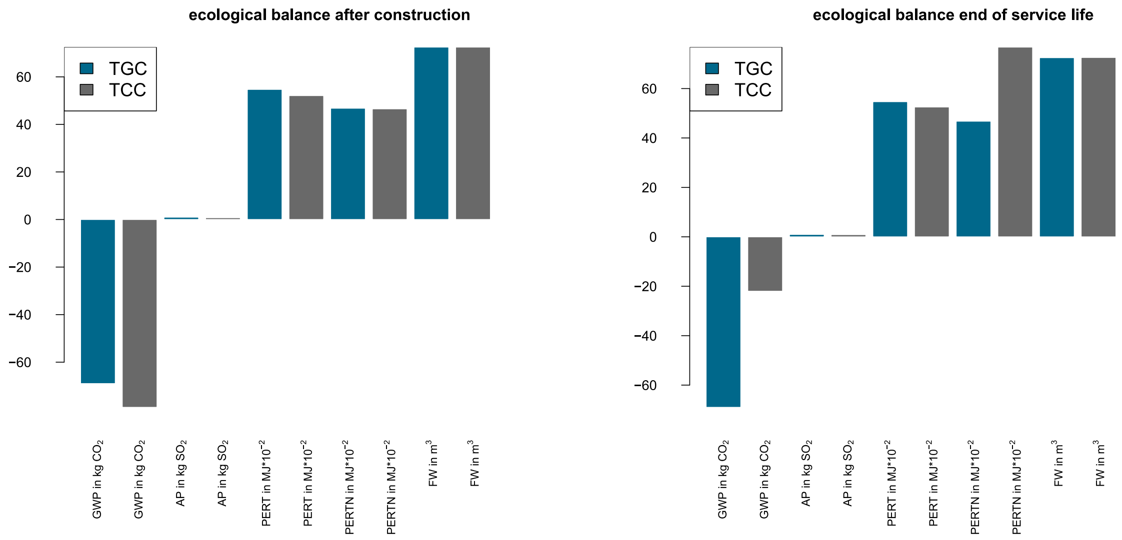

Figure 6: ecological comparison between construction phase and end of service life

3. Composite theory

3.1. General composite theory

In bridge construction, the number of cross sections that can be connected is limited to the bottom chord, usually a block girder made of glued laminated timber and the mineral based top chord. The degree of bonding achieved is limited by the lower barrier *no composite* and the upper barrier *rigid composite*. A *flexible composite* is created between these limits.

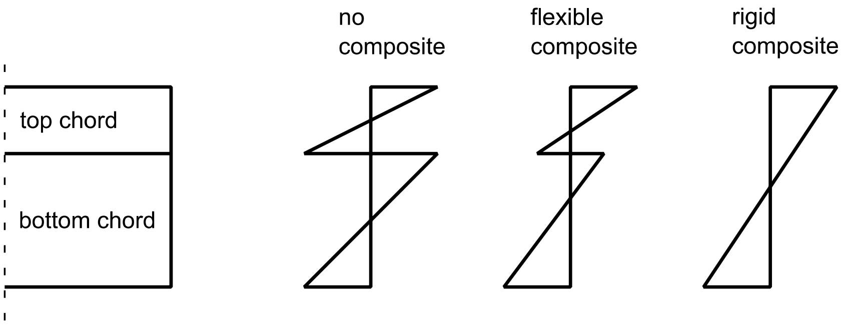

Figure 7: basic strain distributions of a two-part composite cross section

For timber-concrete composite structures in bridge construction, high stiffness of fasteners is decisive. Due to the larger span widths compared to slab structures in building construction, the fasteners need to transmit considerably higher shear forces while retaining a ductile failure. Furthermore, a high fastener stiffness leads to a high degree of bonding of the individual cross section and thus to a more effective use [5]. The aim is to utilize the minimum number of stiff load-bearing fasteners. This results in a discontinuous arrangement of the fasteners over the length of the composite girder with wider fastener spacings. The stiffness of the fasteners is also decisive for the cost effectiveness of a composite solution. To reduces costs in production and assembly as well as achieve a high degree of bonding it required to have as few stiff fasteners as possible.

3.2. Comparison of calculation methods

A discontinuous arrangement of fasteners bears the result that the calculation of the internal forces can no longer be carried out with the common "γ-method" represented in EC 5. Framework solutions are established as an alternative to the calculation of yieldingly connected bending girders. They can be used to map both a continuous and a discontinuous bond in the joint. Depending on the model used, the effort for modelling the frameworks for the representation of discontinuous composite beams can increase considerably.

In order to handle this situation a possible truss model was developed by *Hartmann* and *Kneidel* [6]. In this truss model, the two chords are coupled with flexible diagonals which represent the medium stiffness of the composite. In order to force the same deformation of the chords, they are connected by pendulum rods.

Bergfelder [7] developed a further framework on the basis of a Vierendeel girder. The bond stiffness in the joint is represented in the framework by a flexible cantilever arm. The coupling of the cantilever arms to the top chord is done in a jointed connection to the top chord and to the bottom chord in a rigid connection.

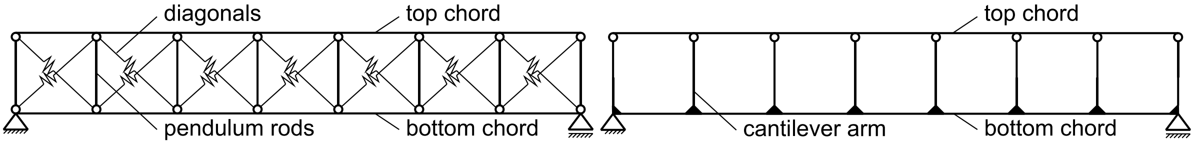

Figure 8: left: truss model, right: Vierendeel girder

Grosse, *Hartnack*, *Lehmann* and *Rautenstrauch* [8] developed a coupling bar system, the basic features of which resemble the Vierendeel girder according to *Bergfelder*. It divides the composite girder into chords with the properties of the individual cross sections and couples these by pendulum rods of infinite stiffness. In contrast to the Vierendeel girder model, cantilever arms with equivalent bending stiffness are placed at the points where the fasteners are attached to the chords and connected by a moment joint. A further framework solution was developed by *Kreuzinger* [9] that differs from the other three framework solutions in its approach to modelling. In contrast to the previous frameworks, the real beams are not represented, but the different stiffness components are assigned to different beams. This model is usually called shear analogy method.

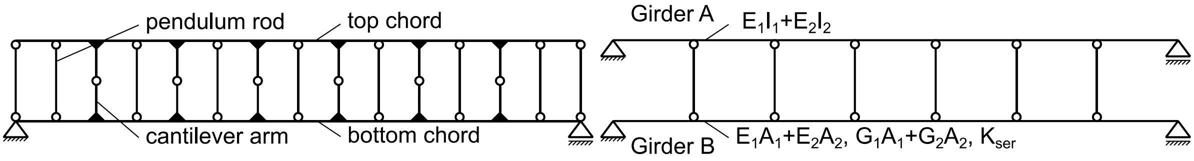

Figure 9: left: coupling bar system, right: model according to *Kreuzinger*

In order to estimate how much the distance between the coupling points influences the accuracy of the results and to check the model's basic suitability for a later calculation they were compared to each other in a parameter study. For the parameter study, a beam on two props with overhang was used as system. For this system, the exact results of the internal forces and deformations from different load cases exist as a solution to the differential equation of yieldingly connected bending girders. The model according to *Bergfelder* for small distances of the coupling points turned out to deliver a deviation of up to 32% at the determined internal forces from the exact result. The shear analogy method showed deviations of up to 9% regarding the internal forces. The framework solutions according to *Kneidel* and *Hartmann* as well as *Grosse* et al. showed only minor deviations of less than 5%.

For the later calculation of the two bridge variants, the coupling bar system according to *Grosse* et al. was selected since this framework solution represents the internal forces and connecting forces more clearly than the truss model. With this model, the internal forces and deformations were then determined for the timber-concrete composite and the timber-granite composite bridge. Both variants including the fasteners were verified in the ultimate limit state of load-bearing capacity and serviceability.

4. Summary and Outlook

A comparison of both variants shows, that if the service life is taken into account there are economic and ecological advantages in favour of the timber-granite composite construction. The renewal of the road surface of the timber-concrete variant leads to higher maintenance costs and worsens the ecological balance with regard to the CO_2 storage potential. In addition it leads to an increase in energy consumption over the lifetime of the timber-concrete composite bridge.

The statical analysis of the two bridges shows that both variants are technically feasible. Furthermore, the timber-granite composite bridge achieved significantly higher stiffness in the final state and thus has a positive effect on the serviceability in the final state. That is due to the lack of creep deformation of the granite at hand. The increase in deformation compared to the initial condition of the timber-granite construction is only 14%. In comparison, the deformation of the timber-concrete construction increases by 80% in the final state. Future projects in the field of timber-granite composites need to investigate the actual behaviour when facing temperature fluctuations. Due to the internal static indeterminacy, the forced stresses from the temperature load might have a decisive influence on the utilisation of the cross sections. Furthermore, the concrete arrangement of the fasteners as well as the exact calculation and illustration of discontinuous composite structures need to be further investigated.

However, the achieved high load-bearing capacity and rigidity, low maintenance costs, and the positive ecological effects over the entire service life shows the superiority of the timber- granite bridge construction over a timber-concrete composite construction. This promises to make further research into the substitution of concrete by granite to be a rewarding endeavour.

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