Semi-precast segmental bridges: Development of a new construction method using thin-walled prefabricated concrete elements

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Abstract
In order to understand the overall picture, the different technologies for the use of thin-walled prefabricated elements in bridge construction as well as the first-time application of them in a bridge project in Austria are described in this paper. Thereafter a newly developed construction method for the on-site fabrication of lightweight box-shaped segments from thin-walled concrete elements, strengthened with steel girders, is explained with the focus lying on the construction of a prototype in a 1:1 scaling. The conceptional design, the manufacturing in a prefabrication plant in Austria and the transport to a construction site are illustrated. Finally, an application example of the new technology is shown based on a design using the incremental launching method. The research confirms the feasibility of the on-site assembly of segments from thin-walled prefabricated elements and that this construction method, once minor constructive details will be solved in the ongoing research project, has great potential for a broad application in bridge construction.

KEYWORDS
bridge construction, concrete, lightweight girder, monolithic bridge girder, post-tensioning, semi-prefabricated, thin-walled prefabricated elements

1 | INTRODUCTION AND STATE OF THE ART

Concrete bridges are usually built by either casting in situ concrete on a scaffolding system, using the incremental launching, or the balanced cantilever method or by varieties of precast erection methods using segments, girders, or complete precast structures. In most cases there is a strict differentiation between in situ casting of concrete and prefabrication, with each construction approach having its specific advantages and drawbacks.

In recent years, several new bridge construction methods have been developed at the Institute of Structural Engineering of TU Wien. The novel bridge construction techniques merge the basic methods, and are therefore a combination of prefabrication and in situ casting of concrete and their attributes. Thin-walled prefabricated concrete elements, such as double walls or semi-prefabricated slab elements are well-known and have been used successfully in building construction for decades. These very light thin-walled prefabricated elements are utilized to rapidly
construct a part of the superstructure before acting as a lost formwork and falsework for later added in situ concrete. After hardening of the additionally placed in situ concrete on top of the prefabricated parts with a rough surface, the whole structure acts as a monolithic superstructure.\textsuperscript{8}

The idea of repurposing thin-walled concrete elements from building construction for the erection of bridges was born during the development of the balanced lift method, where a bridge girder is erected in a vertical position next to the pier before being rotated into its final horizontal position,\textsuperscript{3, 9} very similar to the method of lowering of arch halves. To enable the execution of such a rotation process and to minimize the stresses during the procedure, the weight of the structure must be kept to a minimum. The inventors of the construction method found thin-walled prefabricated elements to be the optimal solution to this problem.

Realizing the potential of the thin-walled elements for bridge construction, with the formwork and falsework in many bridge projects being very expensive (37\% of the costs for the erection of the bridge deck of a medium-span bridge, according to Ref. 10) and time-consuming parts and the construction stages often being crucial for the design of an entire superstructure, especially for long-span bridges,\textsuperscript{11} further approaches for the application were developed at TU Wien. The first technology developed is suitable for the erection of T-beam bridges, which cover spans of up to 50 m,\textsuperscript{1} and is described in Reference 5. In this method U-shaped girders are produced in a prefabrication plant, are then transported to the construction site where they are mounted, installed and filled with in situ concrete, creating the beam part of the T-beam bridge. Once the beams are finished the structure is completed by the deck-slab, by for example utilizing semi-prefabricated slab elements and pumped concrete, as shown in Figure 1(a) or using a formwork carriage as in the bridge described in Section 2.1.

Large-span bridges are usually built using girders with box-shaped cross-sections erected by traditional construction methods\textsuperscript{1, 2} or variations of them. Limitations

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a) U-shaped girders made from thin-walled pre-fabricated elements, taken from Ref. 13; (b) box girder segment made from double wall elements and thin-walled plates\textsuperscript{4}}
\end{figure}
in construction speed or the size of prefabricated parts are set due to the hardening of concrete or the lifting capacities of cranes and the maximum sizes of transports respectively. At the Institute of Structural Engineering of TU Wien different technologies for the construction of box-shaped segments have been developed. These methods do not only combine the advantages of different construction methods such as a monolithic superstructure without continuous joints of in situ casting of concrete and the high construction speed of precast segmental erection methods, but also discard some of their drawbacks such as the need for formwork and scaffolding on the construction site. An example for a prototype segment built from double wall elements and semi-precast slab elements is shown in Figure 1(b).

In this paper, the first-time application of this technology in a bridge project in Austria is described. Moreover, the further development of this technology for the application for large-span bridges is illustrated. Therefore, a newly developed construction method for the on-site fabrication of lightweight box-shaped segments from thin-walled concrete elements, strengthened with steel girders, is explained with the focus lying on the construction of a prototype in a 1:1 scaling.

2 CONSTRUCTION OF FOUR T-BEAM BRIDGES IN AUSTRIA USING THIN-WALLED PREFABRICATED ELEMENTS

2.1 Project description

In 2019 and 2020, during the construction of the new motorway S7 in the southern part of Austria, the rivers Lafnitz and Lahnbach had to be bridged, with one bridge for each direction erected, resulting in a total number of four bridges. The construction site is in a sensitive nature reserve area called Natura 2000, which called for the fulfillment of specific requirements concerning the building lot. Due to the restrictions, the novel balanced lift method was chosen, as it only requires little construction space next to the pier and the abutments and therefore keeps the environmental impact to a minimum, as described in detail in Reference 9. A longitudinal section and top view of the bridges across the river Lahnbach are depicted in Figure 2(a), showing the slender structure with the 72 m long balanced lift section in the center of the bridge. The outer parts of the webs, highlighted in dark grey in the cross sections in Figure 2(b), show the thin-walled prefabricated elements that were used to build the U-shaped girders, which were rotated using the balanced lift method before being filled with pumped concrete to form a solid web in the final state. Due to the rough surface of the prefabricated elements and the use of lattice girders between the prefab and the on-site concrete, both parts of the cross-section can be taken into consideration for structural design calculations. Figure 2(b) clearly shows the small area and thus the small weight of the thin-walled prefabricated girder, which already contains all ducts and a major part of the reinforcement for the final state, in relation to the entire structure.

The successful and practically problem-free first-time application of thin-walled prefabricated elements in bridge construction proves the feasibility of the concept and clearly shows the advantages of this novel hybrid bridge construction method, which not only reduces the dead-load during erection but also allows for a rapid on-site construction.

FIGURE 2 (a) Longitudinal section and top view of the bridges across the river Lahnbach, taken from Ref. 9; (b) cross sections of the bridges across the river Lahnbach, taken from Ref. 9
2.1.1 Construction of precast U-shaped girders

The 72 m long balanced lift section of the bridges was built using six prefabricated parts. The two 18 m long compression struts, the balanced lift girder, consisting of four parts \((2 \times [19.5 \text{ m} + 16.5 \text{ m}])\) and the prefabricated girders with lengths of 9.4 and 20.4 m that were placed between the balanced lift section and the abutments, resulted in a total of eight prefabricated parts which were required for the erection of one web. With each bridge consisting of two webs (16 parts) and four bridges being erected a total number of 64 prefabricated concrete elements had to be produced and transported to the construction site.

U-shaped girders were used in the rotation process as described in Section 2.1.2 and acted as formwork for the subsequently added in situ concrete, as shown in Figure 2(b). All prefabricated elements were produced in the factory of Franz Oberndorfer GmbH & Co. KG in Carinthia in the south of Austria. The production began with the manufacturing of thin-walled concrete slabs on standard casting beds made of steel, as shown in Figure 3(a) whereby a thickness of 70 mm was chosen and the inner surface of the concrete plates was raked to obtain a rough interface for the later added in situ concrete. Once hardened, two slabs were placed upright as shown in Figure 3(b) creating the walls of the individual giders. Between those two standing concrete plates a 120-mm thick bottom slab was cast. That slab connected the two wall elements and created the U-shaped girder as shown in Figure 3(c) taken at the construction site.

2.1.2 On-site construction and transformation process

After the transport of the individual thin-walled U-shaped girders and the hollow compression struts to

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**FIGURE 3** (a) Production of thin-walled prefabricated elements on a standard casting bed and roughening of the concrete surface; (b) upright positioning of thin-walled concrete elements before casting the bottom slab; (c) finished U-shaped girder with all ducts and reinforcement for the additional in situ concrete
the construction site the assembly of the structure began as shown in Figure 4.

The first construction step consisted of placing the two compression struts in a vertical position next to the pier and connecting them to the pier using steel hinges and bolts. After that, the lower parts of the bridge girders were positioned next to the two compression struts, and connected to them, once again with hinges. This construction stage is shown in Figure 4(a). In the next phase, the two upper parts of the two bridge girder halves were placed on top of the lower ones. The joint between the two individual girder parts was filled with grout. Once the grout had reached a compressive strength of 5 MPa, the two parts were connected, turning them into continuous beams (Figure 4(b)).

The two bridge girder halves were tilted inwards and connected to each other at the very top before the rotation mechanism was activated by pushing the compression struts apart using hydraulic jacks (Figure 4(c)). Once set in motion, the structure was slowly lowered by strand jacking systems which had been placed at the top of the auxiliary pier (Figure 4(d)). The lowering process for the girders to reach their final horizontal position took approximately 3 h.

The final position of the girder was aligned before additional temporary tendons between the bridge girder and the auxiliary pier were installed (Figure 4(e)). To stabilize the system the nodes were filled with concrete and the two compression struts were filled with self-compacting concrete pumped in from the bottom to avoid air pockets. The additionally needed girders to span to the abutments were mounted and the joints grouted. With the girder erected and installed the filling with in situ concrete commenced. The girder was symmetrically filled with standard pumped in situ concrete as displayed in Figure 4(e). Simultaneously
post-tensioning tendons were stressed in a targeted manner during the different construction stages.

The cross section as depicted in Figure 2(b) was completed with a deck slab as would be the case for a steel-concrete-composite bridge using a formwork carriage, as shown in Figure 4(f), with a casting section length of 15 m.

3 | APPLICATION OF THIN-WALLED PREFABRICATED ELEMENTS TO BOX GIRDERS FOR LARGE MULTI-SPAN BRIDGES

3.1 | Introduction of the new construction method

Large span concrete bridges are usually erected with a box-shaped girder as this type of cross section offers great resistance against bending around both axis as well as against torsional stresses. According to Ref. 2, bridges with a box cross section are usually built by in situ casting of the concrete or numerous different precast segmental erection methods.

In Reference 12, a new approach for the construction of bridges with a box-shaped girder is described. This method uses precast segments, assembled out of thin-walled prefabricated concrete slabs as shown in Figure 5(a), to build a lightweight bridge girder. For the presented method existing precast segmental bridge construction methods and post-tensioning can be used to assemble the segments on site, as shown for the example of the balanced cantilever method with lifting frames in Figure 5(b). As described for the smaller U-shaped girders in Section 2.1.1 the erected lightweight girder acts as formwork and falsework for the later added in situ concrete allowing the prefabricated elements to become an integral part of the final superstructure.

This novel construction method unites the high construction speed of precast erection with the advantage of

FIGURE 5 (a) Assembly of a lightweight segment; (b) installation of lightweight segments to form a bridge girder, using the balanced cantilever method with lifting frames
a monolithic superstructure without continuous joints from the in situ casting while discarding some of the existing drawbacks of both methods. In segmental erection methods very heavy and large segments must be transported and lifted multiple times, a problem that is no longer existent when using lightweight slabs. In on-site casting of concrete a lot of formwork and falsework is needed which becomes unnecessary when thin concrete elements act as formwork and can bear the loads coming from the fresh in situ concrete.15

3.2 | Prototype box girder bridge segment made from thin-walled elements

3.2.1 | Concept and structural design

To enable the use of lightweight slabs for the on-site construction of box-shaped segments it was necessary to think of connections between individual concrete plates, on the one hand, and of ways to form cross frames within the rectangular box-segments to ensure the stability in transversal direction, on the other.

Taking all the requirements into consideration, it was decided to use thin-walled concrete plates with integrated steel girders as described in Reference 16. The designed system, the so called CLC-slab is shown in Figure 6(a), it uses concrete slabs with integrated steel girders, with corrugated webs, which together act as a composite system against bending and shear stresses. The connection between concrete plate and steel web is ensured by friction and reinforcement bars put through holes within the steel web. This kind of composite construction is already being used in building construction as a complete prefabricated slab with no need of extra on-site concrete and where the openings in the steel girders are used for installation purposes.

When it comes to the application of the concrete-steel-girder-composite slabs in bridge construction, the steel girders come in handy. They cannot only be utilized for the connection of the different slabs among each other but also carry the loads during different construction stages such as assembly or filling with in situ concrete. In addition, the openings in the steel girders prove useful during the placement of the necessary ducts for post-tensioning.

Based on the element choice, a conceptual layout for a segment made from 70-mm thick concrete plates with attached steel girders was designed, as described in Reference 17. The cross section was designed in a way that it could be easily assembled from individually transported plates directly on the construction site (Figure 6(b)). During the development of the design, attention was paid to the construction of rigid connections in the corners that would be simple enough for on-site assembly using standard steel screws.

For the construction of a segment, as shown in Figure 6(b), it was not only necessary to provide rigid connections between the steel girders and the concrete plates but also of the resulting composite beams. The design executed for the prototype is shown in Figure 7. The connection between the corrugated webs and the concrete slabs was solved with a different approach than in Ref. 16 and was provided by two Ø12 mm reinforcement bars welded to the corrugated web, as shown in Figure 7. For the connection between the bottom slab and the web-plate, a steel construction with six M16 8.8 screws was used (Figure 7(a)). The connection between the three individual plates in the upper corner (Figure 7(b)) was solved by integrating a separate steel part, the so-called corner connector, which can also be seen in Figure 6(b) in step 2. In total 22 screws were used to assemble the different elements to the corner connector and provide a rigid connection.
For the structural design, of the described connections as well as the whole segment, several construction stages had to be considered. Each element had to be designed for the lifting process of the thin-walled plates in the precast factory, followed by the transport to the construction site, the assembly to segments and ending with a variety of different construction stages during the construction of the final bridge girder. It is important to note that the stresses during these construction stages depend on the chosen bridge construction method for the installation of the segments.

3.2.2 | Construction of thin-walled elements in a precasting plant

The fabrication of the 70-mm thin concrete plates with embedded steel girders was executed in a prefabrication plant in Austria on a standard casting-bed made of steel. During the production of the reinforcement cage the Ø12 mm reinforcement bars (Figure 8(a)) were welded to the corrugated web girders, which were positioned very precisely in the casting bed afterwards. For the exact positioning, an auxiliary beam, which was temporarily fixed to the beams, was used (Figure 8(b)). With all steel elements in place the concrete was cast until a total thickness of 70 mm was reached. For the construction of this prototype self-compacting concrete was used to simplify the working process and skip the step of compacting the concrete with a concrete vibrator. For an actual bridge project, normal concrete would be used, compacted, and raked as shown in Figure 3(a).

The following morning, all ducts and additional reinforcement (Figure 8(c)), which would be needed on the construction site for all further construction steps, were installed before the finished slab was lifted from the casting bed (Figure 8(d)). With one slab done, the casting bed was directly reused for the next thin-walled plate. The fast production speed was due to highly efficient use of the existing infrastructure in the prefabrication plant. Additional infrastructure was needed making this newly developed bridge construction method not only time but also cost-efficient. The efficiency would additionally rise with a higher number of elements with similar dimensions, as it would be the case if an entire bridge would be constructed using these elements.

3.2.3 | Transport to the construction site

After lifting the thin-walled plates from the casting bed, they can be transported to the construction site. In order to use standard equipment, the dimensions of the individual plates were chosen so that they would fit onto a standard inloader-truck, as used for example for the transport of concrete walls. A drawing of the arrangement of the plates is shown in Figure 9(a) and a truck with the elements during transport in Figure 9(b). Because of the vertical transport position, it is important to foresee lifting points that allow the rotation of the plates into this vertical position and the rotation back into the horizontal position on the construction site. In the case of the construction of the prototype described in this paper, the individual parts where just transported to another hall in a horizontal position, as shown in Figure 8(d).

3.2.4 | Assembly of the segment prototype

With the arrival of the individual plates at the construction site, in the case of the segment prototype this being the adjacent hall, the assembly of the segment could begin. In an assembly area, in proximity to the to-be-erected bridge, the bottom slab is layed down, initiating the assembly (Figure 10(a)). The four corner connectors, needed for the deck slab, are already
attached on top of the web plates and are used for all lifting operations, making auxiliary supports dispensable, which makes a fast assembly possible. Figure 10(c) shows the completion of the box-shaped part of the segment, post-placement of the deck-slab on top of the two web-plates at the time of tightening the screws. The whole segment, with a length of 3.50 m, a height of 2.50 m and a total width of 12.20 m, was completed (Figure 10(d)) once the two cantilever plates were added. This construction step was yet again realized by just using screws and followed by the placement of the additional on-site reinforcement bars needed above the webs on top of the roadway slab. It is important to note, that segments with larger dimensions can also be constructed with the new technology, depending on the bridge construction method used and the local conditions.

The assembly of the segment was executed by two research associates of TU Wien, one master’s student and the crane operator from the factory within 3 h. Although some improvement possibilities, for example, the accessibility of screws at the connections next to the reinforcement, were found during the assembly, this swift execution shows the great time-saving and therefore cost-saving potential of this technology.

During the construction of an actual bridge, the next step following the assembly of a number of segments would be the installation and connection of the individual segments to form a bridge girder. This process will be described in detail in the following section.
3.3 Application of the new segments in bridge construction

Segments built with the new construction principle should be applicable to a variety of existing precast segmental bridge construction methods as for example:

- Balanced cantilever erection by launching gantry
- Segmental span-by-span erection by launching gantry
- Precast full-span erection by launching gantry
- Cantilever erection by lifting frames (illustrated in Figure 5(b))
- Incremental launching method
- Balanced lift method

Within the ongoing research project, the application of the newly developed segments using the previously listed construction methods will be investigated in detail by the means of structural analysis and the development of fast and efficient assembly and construction processes.

The construction principle, when using the incremental launching method, is shown in Figure 11. The initial construction process is similar to the launching of a bridge girder built from fully precast segments. The very heavy concrete parts are replaced by lightweight segments, which are assembled in proximity to the bridge, as described in Section 3.2.4. The joints between the segments get grouted and after reaching a required minimum strength, they are tensioned together to form the bridge girder, which is launched from one abutment, over the piers until reaching the other side of the bridge. When the final position of the structure is reached, the superstructure is completed by adding pumped in situ concrete and post-tensioning, as described for the T-beam bridges in Section 2.1.2.

Due to the use of prefabricated elements that already contain most of the reinforcement for the subsequently added in situ concrete, the time and manpower needed for formwork construction, placement of reinforcement, pouring and hardening of the concrete can be reduced to a minimum, compared to a bridge built with on-site casting of concrete. The time and work saved during launching must be offset against that needed for the additional step of adding the formwork to the inner sides of the web and pumped in situ concrete and tensioning after reaching the final position of the structure. Further investigations into the construction process will give detailed information about the construction time and the expenditure of resources.

During the launching process, the bridge girder must bear alternating negative and positive bending moments, as it is launched over supports and through fields. Figure 12 shows the bending moment envelopes of a girder made from fully precast segments (dashed line) and a lightweight girder constructed from thin-walled prefabricated elements (solid line). The two envelopes were constructed according to Reference 19, taking a launching nose with a length of 60% of the span and a
weight per length unit of 10% of the bridge girder's weight per length unit into account.

The alternating moments during the launching process require a centric prestressing over the whole length of the superstructure, which is directly dependent on the magnitude of the moments and shear forces during the launching process with linear dependence to the self-weight.

The grey area in Figure 12 highlights the differences between the bending moment envelope for the final state (dotted line) and the envelope curve during launching of a bridge girder made from fully precast segments (dashed line). The discrepancy clearly shows that a large part of the centric prestressing required for launching is not needed in the final state and is even detrimental in some areas of the bridge, making it necessary to remove certain tendons, while additional tendons have to be tensioned.

Comparing the calculations of the bridge girder launched with fully precast segments to the one with the thin-walled prefabricated elements, the area of bending capacity only needed for launching is reduced to 16% along the whole bridge girder (hatched area in Figure 12). The reduction of weight and therefore stresses during launching leads to a reduction of centric prestressing allowing for a more efficient design of the overall prestressing system.

Further detailed investigations on the launching process will give a detailed picture about the possible reduction of construction materials, due to the reduction of stresses.

4 | CONCLUSIONS AND OUTLOOK

Based on the numerous technologies developed for the use of thin-walled prefabricated elements in bridge construction and a successfully erected pilot bridge project in Austria, a new approach for box girder bridges made from thin-walled light-weight segments was developed.

The construction of a prototype proved that the concept of assembling lightweight segments directly on the construction site can be a good alternative to in situ casting, allowing for a reduction in formwork, falsework and the laying of reinforcement, as well as to completely prefabricated segments, which often cause problems due to their dimensions and weight during transport, lifting and installation operations and are frequently frowned upon due to the continuous joints in the final state.
By implementing the idea of lightweight segments to different bridge construction methods, several advantages, as for example the reduction of stresses during unfavorable construction stages and a reduction of construction time, can be achieved, as described for the incremental launching method.

In an ongoing research project at TU Wien, the application of lightweight segments to various bridge construction methods, as well as the introduction of prestressing forces into thin-walled concrete elements, the design and load-bearing capacity of joints between such segments and the application of in situ concrete are among others under detailed investigation. The target of these examinations is not only the further development of the method to make it market-ready, but also the profound understanding of the different problematics that arise when working with such lightweight concrete parts in long-span bridge construction.

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