Balanced Lift Method – Building bridges without formwork
Metodo del sollevamento bilanciato – Costruire ponti senza casserature

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ABSTRACT: The balanced lift method is a building bridge method that was developed at the TU Wien. The most common methods to build bridges are the ones using falsework or the cantilever method, but a rather uncommon method, the lowering of arches is seen as the origin of the balanced lift method. The idea was to create a method which would allow a bridge to be built in a very fast manner without the usage of falsework, using prefabricated elements and mounting all parts together in a position – in this case vertically – that would simplify the construction process. In order to reach the final state of the bridge, the vertically assembled parts are rotated into their final horizontal position. This article contains a description of the development of the method, a large scale test will be portrayed and an already designed bridges using the balanced lift method will be shown.

SOMMARIO: Il metodo del sollevamento bilanciato è un procedimento costruttivo per ponti sviluppato nel Politecnico di Vienna. I metodi più comuni sono quelli che usano ponteggi oppure la costruzione a sbalzo, ma un metodo poco usato, quello di calare gli archi, si può considerare all’origine del sollevamento bilanciato. L’idea era quella di un metodo che permettesse una costruzione estremamente rapida, senza l’uso di ponteggi e con elementi prefabbricati assemblati in una disposizione – in questo caso verticale – che semplificasse il processo costruttivo. Per raggiungere la posizione in opera, le parti assemblate vengono fatte ruotare fino alla posizione finale. L’articolo illustra lo sviluppo del metodo, una prova in grande scala nonché i progetti di alcune realizzazioni.

KEYWORDS: precast concrete elements, post-tensioning, bridge construction method, large-scale test / calcestruzzo prefabbricato, post-tensione, metodo costruttivo di ponti, prove in grande scala.

1 INTRODUCTION

When comparing construction methods for arch bridges and regular beam type bridges, it can be observed that in some cases the same construction techniques are used for the production of the arch and the bridge girder. For example in situations when the height above the ground and the size of the arch are not too large the most economical construction will be the one using falsework.

Figure 1 shows the falsework used for the support of the concrete during casting of the arch of the Egg-Graben Bridge. This bridge was designed at the Vienna University of Technology with the idea in mind to create a bridge without mild steel reinforcement in the bridge deck. Post-tensioning tendons encapsulated in plastic ducts and watertight anchorages were used to provide a sound deck slab with a thickness of 500 mm. It could be shown [Berger et al. 2011] that the serviceability and ultimate limit load states according to Eurocode could be fulfilled with this new design approach.

The Egg-Graben Bridge (Fig. 2) was a winning structure of the 2014 competition for the “fib Awards for Outstanding Concrete Structures”. In the statement of the jury [fib 2014] it was mentioned that: “The jury highly appreciated the consistent application of durability philosophy.
The bridge deck is intended to have a long service life with very little maintenance costs because the bridge deck is constructed exclusively with encapsulated post-tensioned reinforcement and watertight anchorage. No other reinforcement is used. Therefore, the electrolytic corrosion in the deck is excluded. In this way water insulation and pavement were also saved. The concrete itself is meant to resist both physical and environmental loads. The bridge also fulfils high aesthetic expectations.”

Another construction method which is frequently used for the erection of concrete arches, is the cantilever method. The bending moments due to the dead weight of concrete during construction are reduced by applying stay cables. The forces in the stay cables can be adjusted in the different construction stages in order to keep the bending moments in the cantilever small. A spectacular example for an application of the cantilever method for arch construction is the Hoover Dam Bypass (Fig. 3). The jury of the 2014 fib Awards for Outstanding Concrete Structures made the following statement about this bridge: “As a result of excellent engineering, the Hoover Dam Bypass bridges the Colorado River at 275 m above the water level. The Hoover Dam Bypass is a breathtaking example of civil engineering in the deep canyon of the Colorado River and its rocky cliffs.”

Yet another method for the construction of concrete arches starts with a vertical production of the arch halves using climbform. At the very bottom of each vertical arch half a hinge is located, which enables a rotation of the arch half from the initial vertical to the final inclined position. Contrary to the cantilever construction method where usually several stay cables are placed on each arch half during construction, only one pair of stays can be attached at one location to an arch half when the method of lowering of arch halves is applied, in order to work with a statically determined structure during the delicate lowering operation. Therefore, larger bending moments, compared to the cantilever construction method, occur in the arch when the lowering of arch halves is applied.

The lowering of arch halves was first applied by Riccardo Morandi in the construction of the Lussia Bridge in 1955 in Italy as described by Troyano (2003). The advantage of this method is the accelerated construction of the arch which can be done quicker in the vertical position using climbform than in an inclined position using a formwork for cantilever construction. Nowadays the method of lowering of arches is regularly applied for bridges in Japan and Spain. Figure 4 shows a picture of the lowering process of an arch half during the construction of the Arnoia Bridge in the year 2012. Each of the two arch halves had a length of approximately 70 m and a weight of 11000 kN.

A tension force of 1100 kN was required in order to move the arch half from the vertical position to an inclined starting position for the lowering process. The cable elongation during the lowering of each arch half was equal to 33 m and the maximum force in each of the two tendons was equal to 2400 kN.

The comparison of construction methods for arches and bridge girders shown in Tab. 1 reveals that there are counterparts for the construction on falsework and the cantilever construction method. However, there was no method with a vertical production of the bridge girder proposed previously. The idea for the balanced lift method was conceived when a construction method was sought which starts with a vertical production of the bridge girders as a counterpart to the method of lowering of arch halves. The balanced lift method is a new construction method. This statement is proven by the patents granted in Germany, USA, Russia, Canada, China, Japan, Australia and Europe.
2 BRIDGE ACROSS THE RIVER LAFNITZ

The design of bridges according to the balanced lift method will be described in this section for the example of two bridges in the south-eastern part of Austria. For the new S7 motorway “Fürstenfelder Schnellstraße” between Riegersdorf and the national border between Austria and Hungary, the rivers Lafnitz and Lahnbach must be crossed. The lengths of the Lafnitz Bridge and the Lahnbach Bridge are roughly 120 meters and 100 meters, respectively. The cross section of the S7 motorway (Fig. 5) in this line section is traced out for two separate directed lanes, therefore the bridges across the rivers should be erected separately each with a width of 14.5 m, regarding prospective reconstruction measures.

The construction areas where the two bridges for the S7 motorway are to be built are ecologically sensitive and part of the nature reserve “Natura 2000”. The bridges are basically needed to cross the rivers and to provide options for a deer pass. To avoid encroachment into the natural habitat, an erection on falsework is not accepted by the highway management company ASFINAG. The construction site should be as small as possible and kept to the central pier and abutments. To meet all these requirements a construction of the bridges would only be possible by the balanced cantilever method, incremental launching or the balanced lift method.

Before the alternative design using the balanced lift method was introduced, the plan was to build the bridges by incremental launching of steel bridge girders (Fig. 6). The cross section was, in order to withstand the bending moments during the launching process, very high compared to the cross section height achieved with the balanced lift method. The big difference in heights, 4.6 m versus 2.0 m, can be achieved due to the compression struts which reduce the span lengths immensely (Fig. 7). The alternative design for the post-tensioned concrete bridges was based on a cross-section with a plate girder as shown in Figure 5. It was proposed to build the central section of the webs by the balanced lift method as shown in Figure 7, to install the end sections of the webs by mobile cranes placed behind the abutments, and to build the deck slab similarly to the original design by a formwork carriage. In the course of the preparation of the alternative design, the abutments and the locations of the central piers were rotated in plan by 30° with respect to the longitudinal axis of the bridge in order to react to the location of the riverbed and to provide an improved design for the deer pass. These changes resulted in a bridge design with two equal spans.

Table 1. Comparison of construction methods for arches and bridge girders / Confronto fra I metodi per archi e per travi

<table>
<thead>
<tr>
<th>Arches</th>
<th>Bridge girder</th>
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<td>Erection on falsework</td>
<td>Erection on falsework</td>
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<tr>
<td>Cantilever construction method</td>
<td>Balanced cantilever method</td>
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<td>Lowering of arches</td>
<td>Balanced lift method</td>
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It could be shown that the construction costs for the post-tensioned concrete bridges erected with the balanced lift method amounted to only 70% of the calculated costs of the composite bridges. When the Austrian highway management company ASFINAG became convinced of the financial benefits from a design based on the balanced lift method, a detailed design for the two bridges for crossing the rivers Lafnitz and Lahnbach was commissioned.

The first steps in the construction process of the S7 motorway bridges will not be any different from using conventional bridge construction methods. The foundations, the abutments and the piers must be
cast. If a bridge with low piers is being built, an auxiliary pier, which is connected to the concrete pier, is needed. The auxiliary pier consists of two sections of a tower crane positioned on both sides of the pier and connected by a platform at the top. The compression struts, which are, in order to decrease weight, made out of hollow reinforced precast concrete elements with small element thickness, are assembled adjacent to the pier (Fig. 8 Construction phase 1). When using the balanced lift method, the weight of the bridge girders during the lifting (for bridges with high piers) or lowering (for bridges with low piers) operations is of utmost importance. This is why not only the compression struts but also the bridge girders are made out of thin precast elements.

To enable the construction of bridges of different sizes and span lengths a variety of bridge girders with different cross sections has been developed. The bridge girders with the chosen cross section are then assembled adjacent to the pier and the compression struts (Fig. 8 Construction phase 2). The bridge girders were designed as U-shaped thin walled prefabricated elements. The wall thickness was equal to 70 mm and the thickness of the bottom slab equal to 120 mm. The bridge girders with a total length of 35.5 m had to be divided into two parts of 19 m and 16.5 m respectively, because of the limited space available at the construction site. The joining of the two parts of the bridge girder is accomplished by a 20 mm joint with high-strength mortar and four monostrands which ensure a compressive stress at the joint in the subsequent construction phases.

In order to start the lifting or lowering operation, two bridge girders must be connected. This is achieved by tilting the bridge girders and by the installation of a tendon consisting of 16 monostrands (Figure 8 Construction phase 3). This tendon, indicated in Figure 8, has to ensure equilibrium during the lowering process by carrying the tensile forces. After the monostrands are slightly stressed, the lowering operation is started.

Similar to the method of lowering of arch halves, which requires that the arch halves are moved from the initial vertical position to a stable starting position for the lowering process, the bridge girders also have to be shifted to a secure starting position. The rotation of the bridge girders from the vertical position to the tilted position shown in construction phase 3 in Figure 8, can be achieved easily by applying small horizontal forces to the top ends of the bridge girders. However, the small change in shape of the mechanism consisting of bridge girders, connecting tendon, and compression struts from construction phase 3 to construction phase 4, has to be carried out in a controlled symmetrical manner, either by pulling at the lower ends of the bridge girders or by pushing apart the compression struts. In order to restrict the works to the area of the central pier only, the second option was chosen. Two hydraulic jacks have to be fixed to the top of the pier. A horizontal force of 20 kN and a stroke of 275 mm for each jack is sufficient to achieve the transformation from construction phase 3 to construction phase 4 of Figure 8.

In construction phase 5 the lowering process is carried out as is shown in Figure 8. The relationship between the total force in the strand lowering units and the vertical movement of the top point of the bridge girders, designated as joint C in Figure 8, is shown in Figure 9. The whole mechanism is a statically determined system during the lowering process like in the method of lowering of arch halves.

An advantage over the method of lowering of arches is the fact that in the balanced lift method all forces are in equilibrium within the structural system consisting of bridge girders, connecting tendon and compression struts and therefore no forces have to be carried by stays and anchored to the ground. A closer examination of Figure 9 shows that the relationship of force and vertical movement is strongly nonlinear and even starts with a negative force of 400 kN. A negative force indicates that in the beginning of the lowering process a vertical force pushing downward on top of the auxiliary pier would have to be applied. After a small movement of only 70 mm this force changes to a tensile force. Obviously, pushing downward at joint C to start the lowering process is an impractical and even dangerous option.
Therefore, a design with two horizontal jacks at the top of the pier was prepared and a method statement was worked out for the interaction between horizontal jacks and strand lowering units. When the maximum stroke of the horizontal jacks equal to 500 mm is reached, the tensile force in the strand lowering units is already equal to 80 kN.

Figure 9. Relationship between total force in the strand lowering units and the vertical movement in Joint C / Diagramma fra forza totale negli stralli.e spostamento verticale del giunto C.

The bridge girders are then slowly rotated to the final horizontal position (Fig. 8 Construction phase 5). The maximum total force in the strand lowering units during this operation is equal to 650 kN and decreases to 150 kN in the final position. The compression struts are crucial to the rotating process. Once the bridge is in its final position, the importance of the compression struts does not diminish, since they become an integral part of the finished bridge. Due to the compression struts the span lengths are decreased therefore enabling a construction of a slimmer bridge in comparison to a bridge without compression struts.

Design drawings of the joints A, B, and C in the starting position and the final horizontal position are shown in Figure 10. The rotation of approximately 75° and 165° at joints A and B, respectively, require careful detailing of the steel plates and the connection to the concrete, taking into account all eccentricities which occur during the change of geometry when the bridge girders are transformed from the vertical starting position to the final horizontal position. The rotations of the bridge girders of approximately 90° at joint C are enabled by a saddle which guides the connecting tendons (Fig. 10).

Once the balanced lift part has been completed the geometry of the bridge girder is corrected by releasing or stressing the connecting tendon. By filling the nodes A and C with in-situ concrete the geometry of the system is frozen. After the installation of temporary tendons (Fig. 8 Construction phase 6) the compression struts and the bridge girders at nodes B are filled with in-situ concrete.

Figure 10. Joints A, B and C before and after the lowering process / Giunti A, B e C prima e dopo l’abbassamento.
The construction phase 7, shown in Figure 8, consists in installing prefabricated bridge girder elements connecting the balanced lift part with the abutments. After adjusting the forces in the temporary tendons, the U-shaped prefabricated elements forming the bridge girder are filled with layers of cast in-situ concrete. Once the concrete has hardened, the temporary tendons are released and the construction phases 1 to 7 are repeated for the construction of the second web of the bridge. The installation of a bridge deck with the aid of a formwork carriage completes the bridge construction (Fig. 5 and Fig. 7).

3 LARGE SCALE TEST OF THE BALANCED LIFT METHOD

In the course of a research project exploring applications of thin-walled concrete elements in bridge construction, it became possible to carry out a large scale test of the balanced lift part of the bridges described in the previous section. The design of all elements (pier, bridge girders, compression struts) was based on a 70 % scale of the designs of the S7 motorway bridges, therefore the test structure had a total length of 50.4 m.

As in the original designed structure the bridge parts were made of thin precast elements in order to keep the weight of the parts, which would be rotated during the balanced lift operation, to a minimum. As explained before, the 25 meter long bridge girder walls consist of 70 mm thick concrete elements which are normally used as slab elements in buildings. The outside dimensions of the cross-section of the bridge girders corresponded exactly with being a 70 % scaled down cross section of the S7 bridges. The girder had a height of 1.26 meters and the width varied from 0.7 m to 1.4 m, with the larger width at the connection points with the compression struts (Fig. 12). However, the thickness of the elements with 70 mm for the side walls and 120 mm for the bottom slab was identical to the design of the bridges for the S7 motorway.

Since the thin-walled bridge girder, consisting only of the U-shaped reinforced concrete and with a weight of 208 kN, would have been too fragile for transport, assembly or any lifting procedures, the cross section had to be enhanced. A truss made of reinforcing bars (transverse bars with a diameter of 20 mm and diagonals with a diameter of 12 mm) were welded to reinforcement bars protruding from the precast side wall elements at the top side of the cross-section. With the help of the truss, the U-shaped cross section was converted into a box section which turned out to be stable enough for all further assembly and lifting operations. To enable future post-tensioning operations and for the installation of monostrands, the bridge girders were equipped with transverse concrete beams.

The transverse concrete beam and the saddle for the tendon at joint C is displayed in the photograph of the end section of the bridge girder (Fig. 11), corresponding to “Detail C” of Figure 10. The transverse concrete beam carried the force of four monostrands. Two of these monostrands were stressed before the bridge girder was transported to the construction site. The other two monostrands were stressed when the bridge girder was assembled in the vertical position. The lifting point is also anchored in the transverse beam as can be seen in Figure 11.

![Figure 11. View of end section of bridge girder / Vista della testata della trave da ponte.](image)

For the compression struts, a U-cross-section would have been impractical during the later filling with concrete, therefore the 13 meter long compression struts were pre-cast as hollow reinforced concrete elements with a width of 1.4 m, a height of 0.875 m and a weight of 15 tons each. The side walls were as thick as the bottom slab of the bridge girders. The top and bottom slabs were cast with a thickness of 112 mm in order to integrate the anchor cones for the tie rods. The tie rods would have the job of carrying part of the concrete pressure during the filling of the hollow compression struts with cast in-situ concrete.

Due to the fact that the S7 bridges are bridges with low piers and this test structure is based on the design of the S7 bridge, an auxiliary pier was needed for the mounting process. For this reason, two 24 m long and 102 kN heavy sections of a tower crane with plan dimensions of 1.2 m by 1.2 m, which would serve as auxiliary piers, were fixed to the foundation slab. Two steel C-profiles were used in order to create vertical guiding rails between the two tower crane sections.
The top parts of the steel profiles were not connected with each other and the distance between the vertical guiding rails amounted to 800 mm.

The hinge connection in the bottom of the structure consisted of 30 mm thick steel plates at the ends of the compression struts and concrete filled steel tubes with an outer diameter of 150 mm placed on the foundation. The steel plates had to be positioned very accurately on the concrete filled tubes to provide a proper hinge connection. After the compression struts had been placed in a correct position they were temporarily fixed to the pier and the auxiliary piers.

The prefabricated bridge girders could then be transported from the prefabrication plant to the stockyard. A 100 ton mobile crane lifted one bridge girder after the other (Fig. 12) to be fixed to the top end of the compression struts using four 16 mm bolts. Even though the cylindrical openings in the joining steel plates only had a tolerance of 1 mm the assembly operation was carried out without any problems. A close-up view of the connection of the bridge girder to the compression strut, which corresponds to “Detail B” in Figure 10, can be seen in Figure 13.

After only four days of assembly, the bridge was ready for the balanced lift part of the construction process. In order to start the rotating process, the bridge girders had to be tilted so that the top ends would touch each other. Subsequently, twelve monostrands were installed in the two bridge girders. The monostrands were anchored at the connecting points of each bridge girder with the compression struts. In the top section of the bridge girders, circular saddles with a radius of 544 mm had been formed during pre-casting (Fig. 11). After the installation of the twelve monostrands, the strands were slightly stressed to prevent sagging.

The lowering process was achieved by slowly and simultaneously lowering the two top points of the bridge girders with the aid of two mobile cranes (Fig. 14). The maximum lifting force, which had been calculated to 270 kN, corresponded well with the lifting force measured by the cranes.

After the bridge had been rotated from the vertical into the horizontal position, the geometry of the structure was checked. By stressing or relaxing the installed monostrands the geometry of the structure could be easily adjusted. This turned out to not be needed since the test structure’s geometry was within an acceptable range (Fig. 15 and Fig. 16).
With the aid of the large scale test it could be demonstrated that the balanced lift method works and that the joint details can be built using simple connection details with steel plates and bolts (joint B) and a saddle with tendons (joint C). The radius of the tendons at joint C is much smaller than in usual post-tensioning applications. The reduction of the ultimate force as a function of the curvature of the saddle was determined experimentally [Kollegger et al. 2012]. It could be shown that the monostrands do not lose load carrying capacity even for a small radius of only 0.5 m.

Figure 15. Large-scale model of the balanced lift part of the Lafnitz Bridge/ Modello in grande scala della parte sollevamento bilanciato del ponte Lafnitz

Figure 16. Bridge girder with 70 mm prefabricated wall elements / trave da ponte con sponde prefabbricate spesse 70 mm.

4 CONCLUSIONS

By employing the balanced lift method, the spans of the bridge girders are reduced by the compression struts, thus enabling considerable savings in construction materials. The proposed method will be especially advantageous for bridges with high piers and span lengths between 50 and 250 m. The usage of temporary piers enables an economic application of the balanced lift method for bridges with piers of modest height, as for example the two bridges on the S7 motorway.

Another advantage of the balanced lift method is the fact that all assembly and mounting operations are concentrated at the pier and that the rotation of the bridge girders can be carried out much faster than by horizontal launching of the bridge girders. The small space requirements and the high construction speed might be of advantage when an obstacle like a railway line or a busy motorway has to be spanned by a bridge and the interruption of the traffic routes has to be kept to a minimum.

Con l’impiego del metodo del sollevamento bilanciato, le luci delle travi dei ponti vengono ridotte dai puntoni, permettendo così un risparmio di materiali. Il metodo proposto è particolarmente vantaggioso per ponti con pile alte e luci tra 50 e 250 m. L’uso di pile temporanee consente un’applicazione economica del metodo in ponti di modesta altezza, come ad esempio i due ponti sull’autostrafa S7.

Un altro vantaggio del metodo è che tutte le operazioni di assemblaggi e montaggio sono concentrate sulla pila e che la rotazione delle travi può essere molto più rapida della costruzione in avanzamento. Lo sazio limitato richiesto e l’elevata velocità di costruzione possono essere vantaggiosi quando ostacoli come autostrade o ferrovie debbono essere scavalcati riducendo al minimo le interruzioni dell’esercizio.

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