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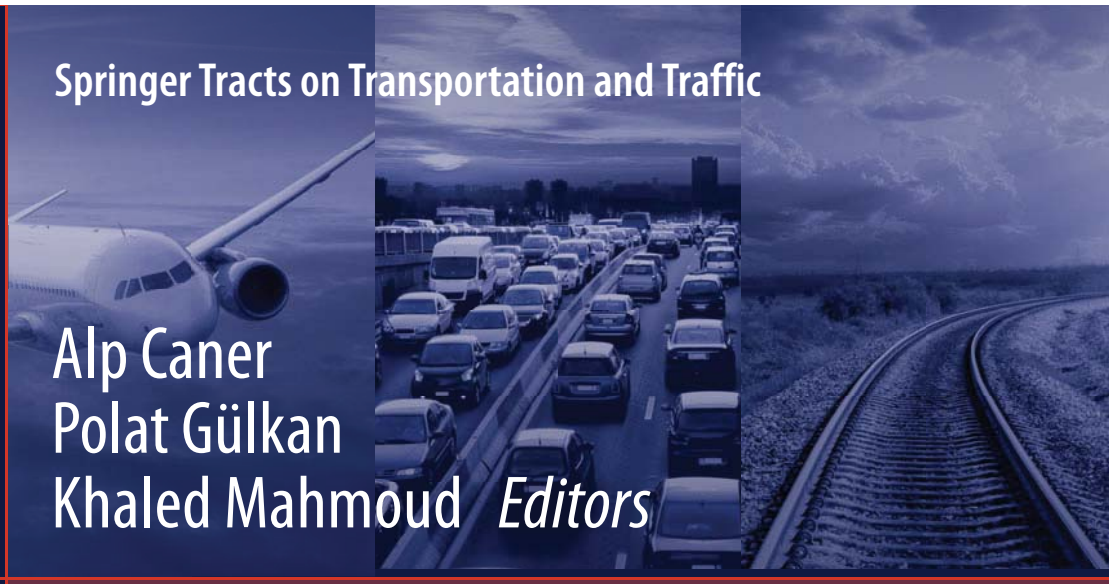

Alp Caner
Polat Gülkan
Khaled Mahmoud *Editors*

Developments in International Bridge Engineering

Selected Papers from Istanbul Bridge Conference 2014

Springer

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Volume 9

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Editors

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Preface

The movement of people, goods, and services between urban settlements and production facilities is the essential circulation that keeps regional and national economies running. Bridges are the vital connectors that ensure that transportation systems function safely and economically as intended by those who have planned and conceptualized them. Bridge engineering is a special discipline within structural engineering that focuses on the design, construction, erection, assessment, and maintenance of these connectors for the benefit of society. Bridges are often durable symbols of technical prowess, economic power, and esthetic refinement. Just as many ancient bridges that have become landmarks evoke in us a sense of amazement at the creative skills of the old masters who built them, so do their younger counterparts that display the flair of more recent builders who have combined advanced analysis techniques with modern, high-performance materials to craft structures that defy the heretofore unchallenged limits in terms of span, height, or frugal use of material resources. Its many counterexamples notwithstanding, bridge engineering is indeed a uniquely singular parade arena to display technical experience and artistic maturity. It is sometimes a shared responsibility among engineers and the special breed of architects who have the craftsmanship to improve the technical attributes of the finished product. We hope that this book will serve to give its readers an overview of the many problems that must be resolved to produce bridge structures that will meet the challenges they will face during their service lifetime.

The Turkish Group of the International Association for Bridge and Structural Engineering (IABSE), in collaboration with Middle East Technical University (METU), the Turkish General Directorate for State Highways (KGM), the General Directorate for State Railways (TCDD), the Turkish Contractors Association, the Turkish Association for Structural Steel (TUCSA), the Turkish National Committee for Roads (YTMK), the Turkish Association for Seismic Isolation, the International Association for Earthquake Engineering (IAEE), the Transportation Research Board (TRB), American Concrete Institute (ACI), the Bridge Engineering Association, and SIBERC served as host for the Istanbul Bridge Conference during August 11–13, 2014. The conference was generously supported by many sponsors, AGM, Arsan

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Kaucuk, Aydiner Inc. Company (Aybet), BERD, Besmak, Cengiz Nurol, Chodai Co., Computers and Structures, Inc. (CSI), DOKA, DUYGU Engineering, EMAY International Engineering and Consultancy Inc, EM-KE, Endem Construction, EPO Construction Chemicals, FIP Industriale, FREYSAŞ, IC İçtaş Construction Co, Ilgaz İnşaat, INPRO, JOTUN, KMG Project, KOBA Engineering and Consulting Co. Ltd, LARSA, MAGEBA, Mapa İnşaat ve Ticaret A.Ş., Maurer Söhne GmbH & Co., MEGA Engineering Consulting Co., Mistras Group, MOOG Gmbh, Otoyol Yatırım ve İşletme A.Ş., Ozdekan Rubber Company, PERİ, Pitchmastic Pmb Ltd, Sismolab, Strainstall, TEMELSU International Engineering Services, TESTART, TNO Diana, TTS International Engineering and Architecture, WireCo Structures, Wowjoint, Wuhan HIRUN Engineering Equipment Co., YAPIFEN Engineering, and Yüksel Proje.

iBridge was attended by **250** participants representing **30** different countries. The conference program included **96** papers. It was complemented by a visit to the construction site for the third Istanbul Strait crossing, a major project that will place the bridge among the top five long-span bridges in the world in several categories when it has been completed.

The 19 papers selected for this book represent a cross section of the breadth of the topics that were taken up in the conference. The selection has been made on the basis of scientific and technical relevance, timeliness, and expected added value for practitioners. A few authors who were invited to finalize their papers for inclusion in the book failed to do so on time, and a few others were eliminated because they had been submitted elsewhere for publication. The papers represent current concerns in bridge engineering as they exist in many countries and the solutions for those issues that have been arrived at under codified constraints that have echoes in other locations. Theory, experiment, and practice are presented in balanced proportions in the texts that follow.

We have grouped them under four broadly defined thematic areas as follows:

- "Modeling and Analysis" (7 papers)
- "Construction and Erection Techniques" (3 papers)
- "Design for Extreme Events" (4 papers)
- "Condition Assessment and Structural Health Monitoring" (5 papers)

The book has been divided into four principal sections along these themes.

The editors would like to acknowledge the excellent cooperation that they have received from the authors in revising their papers according to reviewer comments and the tens of reviewers, from the Scientific Committee as well as externally named experts (many in multiple assignments), who willingly gave much of their time in examining the papers for their content to ensure that this would be a printed source with a positive impact, and provide guidance for their colleagues in the broader engineering community. The editorial staff at Springer Publishers has been unfailingly helpful in guiding us toward producing a book in their style.

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We have received invaluable support from the staff at INTERCON that served as the Conference Secretariat and doubled as providers for the initial screening process of the written contributions.

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Balanced Lift Method—A New Bridge Construction Technique

J. Kollegger and S. Foremniak

Abstract The economic performance of concrete bridges can be improved in certain design situations by using the balanced lift method, a new bridge construction method developed at the Vienna University of Technology. This method proposes to build the bridge girders in a vertical position and to rotate them into the final horizontal position with the aid of compression struts. The compression struts decrease the span of the bridge and allow lighter bridge girders, compared to bridges built by the balanced cantilever method or incremental launching, to be obtained. The balanced lift method can be applied for bridges with high and low piers enabling the construction of bridges over deep or low valleys. The first application of the new method is the construction of two bridges with low piers for the Austrian road management company (ASFINAG) crossing the rivers Lafnitz and Lahnbach on the S7 motorway in the south-east of Austria.

1 Balanced Lift Method

In conventional applications of precast concrete elements in bridge engineering, either match-cast elements are installed by using gantries or heavy bridge girders are lifted with mobile cranes [1, 2]. In a research project at the Vienna University of Technology a different approach was investigated called the balanced lift method. The main advantages of the balanced lift method are enabling an accelerated construction by using precast elements and decreasing the spans of a bridge through the usage of compression struts. The underlying idea was to construct the whole bridge in a vertical position and then rotate the bridge girders from the vertical into the final horizontal position with the aid of compression struts. A quick

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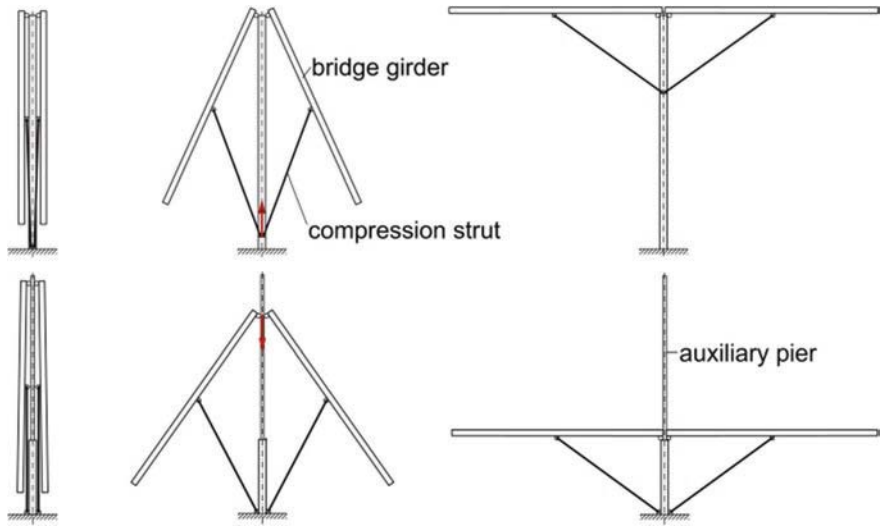

Fig. 1 Balanced lift method for high bridges *top*. Balanced lift method for low bridges *bottom*

way to describe this bridge building method is by comparing it to the process of opening an umbrella—with the bridge girders being the ribs and the compression struts being the stretchers. The compression struts are important load carrying members during the construction process and also in the finished bridge structure. As a result, much lighter bridge girders are obtained compared to bridges built by the balanced cantilever method or incremental launching.

The method has been primarily invented for bridges over deep valleys, meaning bridges with high piers, but can be—with minor changes—used for bridges with low piers. The example displayed in Fig. 1 (top) is suited for a valley bridge with high piers. The application of the balanced lift method for bridges with piers of small height is possible, if an auxiliary pier is used as is shown in Fig. 1 (bottom). The amount of force that is needed for the rotation process during the bridge construction depends, if one sets friction and eccentricities aside, on the weight of the bridge girders and the compression struts. Due to the importance of the weight of the different bridge elements the Institute for Structural Engineering at the Vienna University of Technology started working on different approaches for the usage of thin precast elements in collaboration with in situ concrete. The underlying idea is to minimize the weight of precast elements during transport and lift operations, then filling the elements with in situ concrete to create monolithic structures. Due to the very competitive costs compared to in situ concrete, the precise executions and the economic value, using precast elements reduces not only the construction period but also construction costs.

The international patent application procedures for the balanced lift method are running smoothly. The discussions with the examiners are restricted to formal issues and national peculiarities in the respective patent laws. Patents have been issued for Germany (DE 10 2006 039 551), USA (US 7,996,944), Russia (RU 2436890),

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China (CN 1204627), Japan (JP5302195), Australia (AU2007288151) and Canada (CA2661311). The patent application procedures in Europe, Norway and India are still in progress. The first application of the new method is the construction of two bridges for the Austrian road management company (ASFINAG) crossing the rivers Lafnitz and Lahnbach on the S7 motorway in the south-east of Austria.

2 Application of Balanced Lift Method for Low Bridges

When designing bridges with low piers constructed with the balanced lift method one must keep in mind that the span of the balanced lift part must be held between 40 and 80 m [3]. Due to these small spans, a plate girder with a pre-fabricated bridge girder as shown in Fig. 2 is convenient as a cross section. In this case, the balanced lift method substitutes a construction either by incremental launching or by using falsework [4].

The design of bridges with piers of small height according to the balanced lift method will be described in this section for the example of the bridge across the river Lafnitz in the southeastern 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 and 100 m, respectively. The cross section of the S7 motorway (Fig. 2) 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

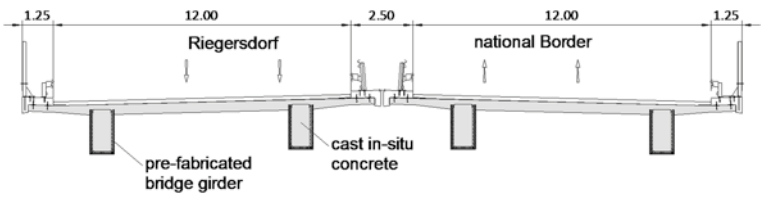

Fig. 2 Cross section of the S7 bridges

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(Fig. 3). 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 versus 2.0 m, can be achieved due to the compression struts which reduce the span lengths immensely (Fig. 4). The alternative design for the post-tensioned concrete bridges was based on a cross-section with a plate girder as shown in Fig. 2 [5]. It was proposed to build the central section of the webs by the balanced lift method as shown in Fig. 4, 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.

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.

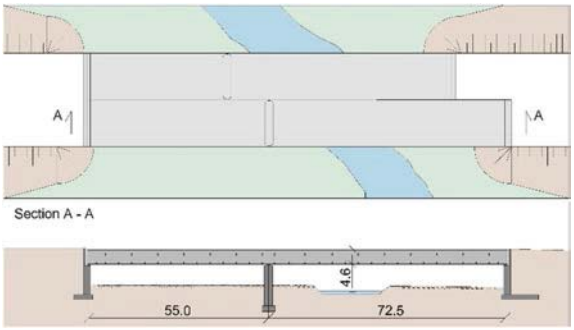

Fig. 3 Original design: a steel-concrete-composite bridge over the river Lafnitz

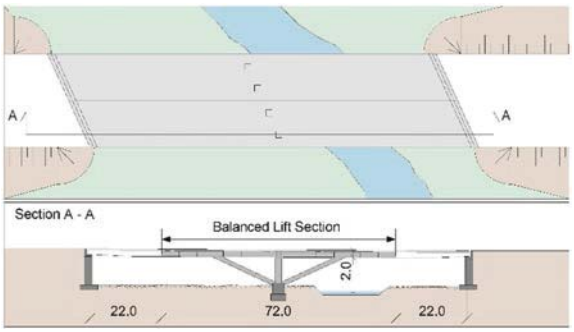

Fig. 4 Design based on the balanced lift method for a post-tensioned concrete bridge over the river Lafnitz

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2.1 Large Scale Tests

During the design of the S7 bridges it was decided to construct a bridge test structure with a total length of 50.4 m. The design of the test structure was based on a 70 % scale of the design of the S7 bridges. Scaled down hollow reinforced concrete elements with small element thicknesses were prepared for the different elements of the bridge. For the 25 m long bridge girders, the side walls were 70 mm thick concrete elements. These elements were assembled on a steel form and then connected by a 120 mm thick slab of reinforced concrete. The height of the U-shaped sections of the 25 m long bridge girder was 1.26 m but the width varied from 700 mm to 1.4 m; the larger width was required at the point of connection with the compression strut.

The thin-walled bridge girder with its U-shaped cross section would have been too fragile for transport, assembly and the lifting process. Therefore, a truss made of reinforcing bars was welded to reinforcing elements protruding from the precast side wall elements at the top of the U-section. The U-section was hence converted to a box section which proved very robust in assembling and lifting operations. For the installation of tendons, the bridge girders were equipped with transverse concrete beams for future post-tensioning operations. Two 25 m long sections of a tower crane, equipped with guide rails, served as an auxiliary pier. Figure 5 shows the assembly of the compression struts in the vertical position. The bottom ends of the compression struts were equipped with 30 mm thick steel plates which were positioned quite accurately on concrete-filled steel tubes with an outer diameter of 150 mm, to provide an inexpensive hinge connection. The lifting of the second bridge girder is shown on the right of Fig. 5.

The lowering operations of the top points of the bridge girders with the aid of two mobile cranes are shown in Fig. 6. The maximum lifting force had been calculated at

Fig. 5 Auxiliary pier and assembly of compression struts with the aid of a mobile crane *left*. Assembly of the second bridge girder *right*

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Fig. 6 Lowering of the top points of the bridge girders with the aid of mobile cranes

270 kN, which corresponded well with the lifting force measured by the cranes. On a real bridge, the compression struts would then be filled with cast in situ concrete. In this case, where the structure is intended as a demonstration project, only the node above the pier was filled with concrete to provide some wind resistance.

2.2 Designs According to the Balanced Lift Method for Bridges with Low Piers

In the last years, several additional conceptional bridge designs according to the balanced lift method have been prepared. As an example, the two bridges for the city bypass of Wieselburg are shown in Fig. 7. The cross-section for the bridges was designed as a plate girder with a width of 16 m, quite similar to the bridges on the S7 motorway described above. The location of the bridges is also situated in an environmentally sensitive area and it could also be shown to the owner that the application of the balanced lift method would have economic advantages compared to a design based on the incremental launching of steel girders.

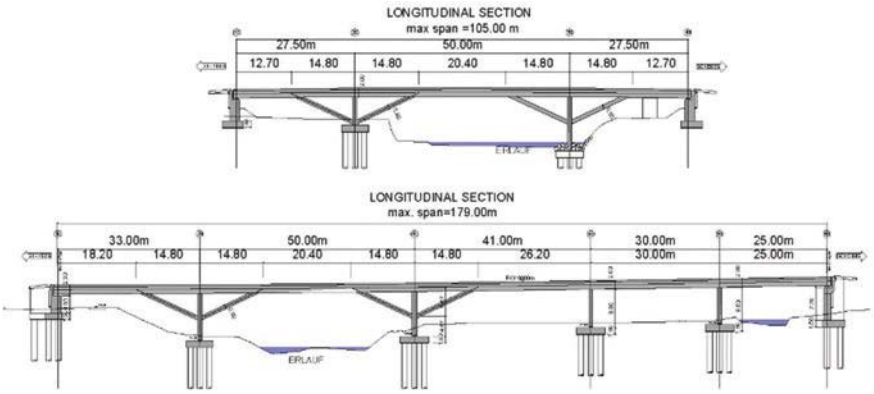

Fig. 7 Bridge design of two Erlauf bridges according to the balanced lift method

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3 Application of Balanced Lift Method for High Bridges

When designing bridges with one high central pier constructed with the balanced lift method spans from 40 up to 125 m can be achieved. In this case the balanced lift method substitutes the balanced cantilever method. San Leonardo viaduct (Fig. 8) is a perfect example for a bridge that could have been constructed by the balanced lift method with one central pier only. The San Leonardo viaduct has two equal spans of 105 m. The bridge was built from 1968 to 1970 as part of the Palermo-Catania motorway in Sicily. If a deep and wide valley is spanned the balanced lift parts can be added enabling spans from 100 to 250 m (Fig. 9). In comparison to the plate girder cross sections of the bridges with low piers box girder cross sections are needed for spans larger than 100 m.

3.1 Bridge Girders Out of Hollow Wall Elements and Ultra-Thin Precast Elements

As it has been mentioned before the weight of the bridge girders and compression struts is of utmost importance during the lifting operation. Due to the large spans of the bridges bigger cross sections must be constructed. Therefore the cross sections as used for the S7 bridges could not be applied, but the idea of using precast elements in collaboration with in situ concrete was refined to create light box girders.

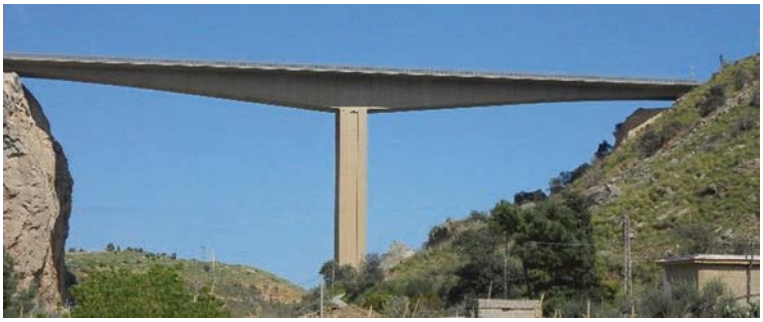

Fig. 8 San Leonardo viaduct in Sicily

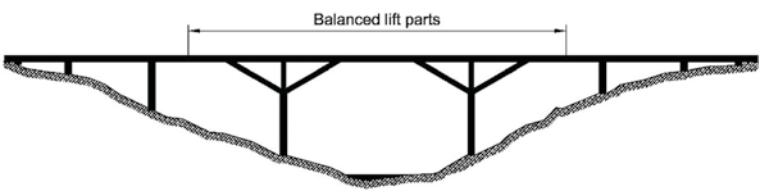

Fig. 9 A bridge across a deep, wide valley

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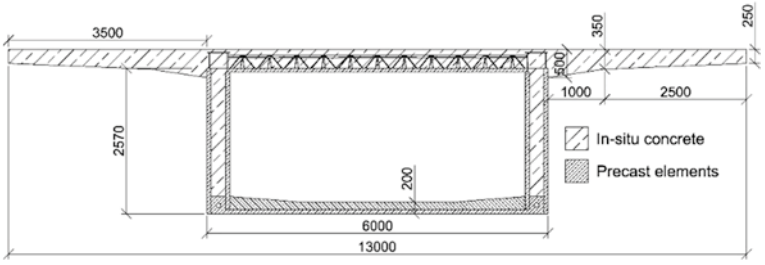

Fig. 10 Cross section of the bridge girder out of hollow wall elements and ultra-thin precast elements

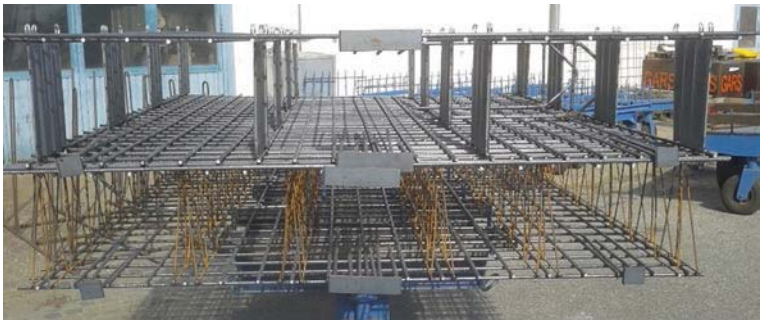

Fig. 11 Reinforcement cages for the hollow wall elements. *Top* reinforcement cage using curved steel elements. *Bottom* reinforcement cage using lattice-girders

The webs of the bridge sections are made out of hollow wall elements and are held together by ultra-thin precast elements. In this state, the elements only have one fourth of the weight of a finished bridge girder with the same length (Fig. 10).

For a research project, two sections, each with a different kind of separation-reinforcement in the hollow wall elements, were built and tested. One set of hollow wall elements, which are used as the webs of the bridge girder, were manufactured using conventional lattice-girders (Fig. 11), the second set used curved steel elements (Fig. 11).

The construction of the precast elements starts with the manufacture of the webs. The hollow wall elements are manufactured fully automatically on a rotary production. Owing to the production process, the maximum width of the hollow wall elements is limited to 500 mm, the maximal height and length are limited to 3.40 and 12.00 m respectively. Due to limited space between the two slabs of the hollow wall element, all reinforcement and all of the ducts required for subsequent prestressing should be attached to the reinforcement cage before the hollow wall elements are cast.

While the wall elements are being manufactured the reinforcement cage for the floor slab and the deck slab can be produced. To reduce the weight of the precast section the floor slabs width is held to a minimum of 70 mm, with a stabilizing beam every two meters to strengthen the slab. The hollow wall elements are placed upright on a casting table and the floor slab including the stabilizing beam are cast

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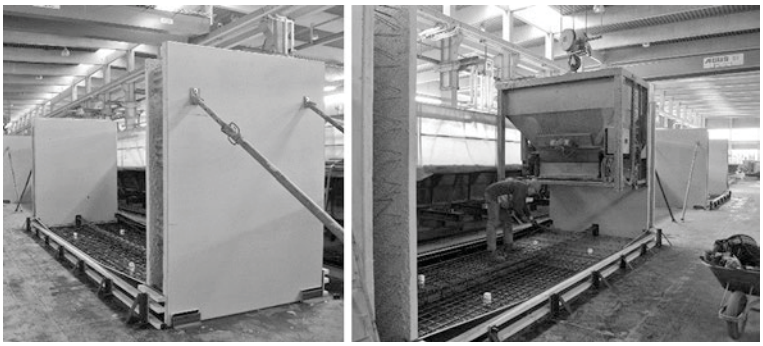

Fig. 12 Hollow wall elements are placed upright and the reinforcement cage for the floor slab is installed *left*. Casting of the floor slab *right*

Fig. 13 Deck slab on the casting table *left*. The finished precast bridge girder *right*

(Fig. 12), creating a u-shaped section. The length of the bridge girder segments is not limited by the length of the hollow wall segments (12 m). The hollow wall elements can be put side by side before the floor slab is cast, therefore creating a bridge girder segment with any desired length.

The deck slab is cast separately on a casting table with a stabilizing beam out of steel [Fig. 13 (left)]. After hardening the deck slab can be placed on top of the u-shaped section. Through welding parts of the deck slab and the stabilizing beam together with the u-shaped section, the precast bridge girder has reached its final state and is ready for transportation [Fig. 13 (right)]. Once the precast elements reach their destination and are installed in their final position, the filling of the floor slabs and the hollow wall elements with in situ concrete can begin. For the casting of the deck slab the thin precast element must be supported.

3.2 Large-Scale Tests on the Bridge Girders

Large-scale tests were used to provide valuable insight into the stability of the girders and for checking how precisely the weight of the actual girders corresponded with the calculated weights. The experimental girders were subjected to loading tests to assess their performance during transport and lift operations. The experimental setup of the large-scale tests is shown in Fig. 14.

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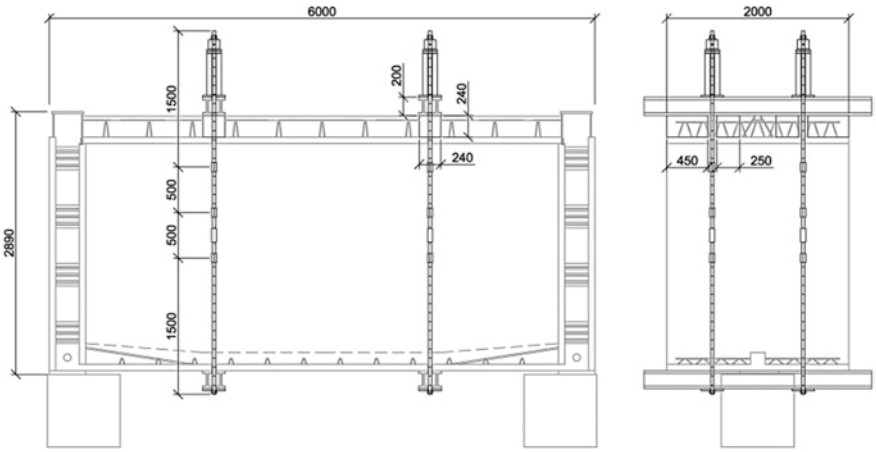

Fig. 14 Test setup in longitudinal and in profile

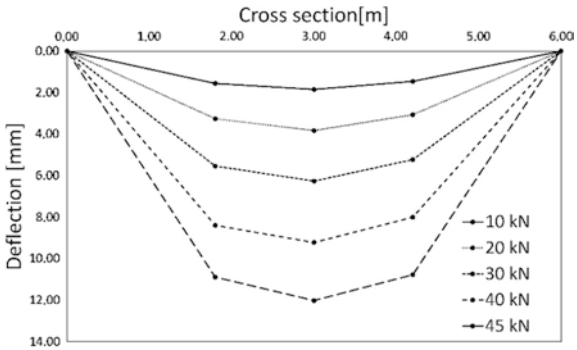

Fig. 15 Deflection of the deck slab during 5 load steps

The bridge girder sections were placed on 3 bearings and the load was applied with four hydraulic jacks. In order to apply a linear load instead of a punctual load the jacks were placed on wooden beams. The deflection of the deck and floor slabs was measured with a set of linear variable differential transformers (LVDT's). Each precast bridge girder section was instrumented with 18 LVDT's, of which nine LVDT's measured the deflection of the deck slab and the other nine measured the deflection of the floor slab. Both precast bridge girder sections demonstrated the same load bearing behavior.

Since the only goal of the test was to provide an insight into the stability of the sections the experiment stopped at a load of 45 kN. At a load of approximately 45 kN the maximal measured deflection of the deck slab was approx. 12 mm. The mean of the deflections of the deck slab in correlation with the load is shown in Fig. 15. The stiffness of the precast bridge girder sections can be therefore calculated to be EI = 7.9 MNm^2. The results confirm that the elements have enough stability to be transported and installed but will need extra support while the deck slab is being cast.

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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. Different cross sections out of thin precast elements have been developed and tested allowing a construction of bridges with the balanced lift method in lengths between 50 and 250 m.

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