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THE RECENTLY BUILT POLISH LARGE ARCH BRIDGES – A REVIEW OF CONSTRUCTION TECHNOLOGY

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Arch bridges are built since two thousand years at least. Structural materials changed during this time. The design methods were changed also. The biggest impact was noted with development of Finite Element Method and graphical methods of preparation of technical drawings which is strictly combined with development of computers. These processes appeared also in Polish construction industry, especially from the beginning of 90-ties XX century.

But in this paper we do not consider mentioned above problems. We would like to present development of arch bridges from construction technology point of view. This aspect of creation of bridge structures is not very often the subject-matter of analysis. For many investors, design engineers and contractors optimization of structures is most important issue. For most of them the reduction of volume (weight) of structural material is only solution. But sometimes it is not true – the construction technology gives much more efficient results.

We present below examples of realization in Poland medium and large span arch bridges – steel, concrete and hybrid structures.

Keywords: Bridge, Viaduct, Arch bridge, Construction technologies

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1. INTRODUCTION

There is no doubt that arch bridges are beautiful, functional, and a pleasure for the motorist to drive over. Long-span arch bridges over deep valleys and in the cities have no competitors as far as aesthetics is concerned. Therefore they have become very popular. Arch bridges are better looking than beam and truss bridges. Many of the contemporary arch bridges built for the last 20 – 30 years are in the middle of cities whose residents consider these bridges not only necessary for commerce but also their beautiful appearance [7, 16].

Arch bridges have been built for two thousand years at least. Structural materials have changed during this time, from stone to FRP composite. The design methods have been also changed; the biggest impact has been noted recently with the development of computers and relevant software, based mainly on Finite Element Method (FEM) and Computer-Aided Design (CAD) codes. These processes have appeared also in the Polish construction industry, especially after the change of economic system at the beginning of 90-ties of XX century.

In the paper, the construction technologies of arch bridges, recently built in Poland, have been presented. This aspect of arch bridge development is not very often the subject-matter of technical reviews. For most of designers and contractors, the material mass reduction is the only aspect to be considered in bridge design. However, the erection technology plays a very important role in bridge cost optimization and can give much more efficient results. The examples supporting the above-mentioned statement have been described in the text in the following chapters, taking into account both concrete and steel arch bridges.

2. CLASSIFICATION AND CONCEPTUAL DESIGN OF ARCH BRIDGES

There are many different types and arrangements of arch bridges [12]. A deck arch is one where the bridge deck is located above the crown of the arch. The deck arch is also known as a true or perfect arch. A through-arch is one where the bridge deck is located at the spring line of the arch. A half-through arch is where the bridge deck is located at an elevation between a deck arch and a through arch. A further classification refers to the articulation of the arch. A fixed arch implies no rotation possible at the supports. A fixed arch is indeterminate to the third degree. A three-hinged arch that allow rotation at the supports and in the crown and is statically determinate. A two-hinged arch allows

rotation at the both supports and is statically indeterminate to one degree. A tied arch is one where the reactive horizontal forces acting on the arch ribs are supplied by a tension tie at deck level of a through or half-through arch. One proposal for arch bridges is to prestress the tie girder with prestressing tendons. Another is to have the deck participate with the tie girder. The tension tie is usually a steel plate girder or a steel box girder and, depending on its stiffness, is capable of carrying a portion of the live loads. A weak tie girder, however, requires a deep arch rib and a thin arch rib requires a stiff deep tie girder. Since they are dependent on each other, it is possible to optimize the size of each according to the goal established for aesthetics and/or cost.

While most through or half-through arch bridges are constructed with two planes of vertical arch ribs there have been a few constructed with only one rib with the roadways cantilevered on each side of the rib. Hangers usually consist of wire ropes or rolled sections. The hangers are usually vertical but truss-like diagonal hangers have also been used. Diagonal hangers result in smaller deflections and a reduction in the bending moments in the arch rib and deck. The inclined hangers with multiple intersections make the network arch bridge act like a truss, with only axial compressible and tensile forces. Bending moments and shear forces are very small in network arches. The hanger arrangement is what separates network tied arch structures from other types of tied arches, such as those with vertical hangers. It is defined by the number of hangers, hanger inclination and hanger distance. There have also been arch bridges constructed with the arch ribs tilted so they can be connected at the crown. This is done for aesthetic reasons but it does add to the lateral stiffness of the arch bridge and could result in reduced bracing requirements.

By deck is meant the roadway concrete slab or orthotropic steel plate and its structural supports. The rise-to-span ratio for arches may vary widely because an arch can be very shallow or, at the other extreme, could be a half-circle. Most arches would have rise-to-span ratios within the range of 1:4.5 to 1:6. Steel arch ribs are usually made up of plates in the shape of a rectangular box. The ties are usually either welded steel box girders or plate girders. After the moments and axial forces become available from the three-dimensional finite-element nonlinear analysis the arch elements, such as the deck, ribs, ties, hangers, and columns can be proportioned. Table 1 contains information suitable for conceptual design. It shows relation between structural material and form with position of the deck, slenderness and length of span.

Table 1. Preliminary data for conceptual design [16]

| Structural material | Structural form | Position of the deck | Slenderness f/L | Ratio h/L |
|---------------------|------------------------------------|----------------------|--|--|
| Concrete | Fixed and pinned at both ends | Upper deck | $1/3 \div 1/7 L$ | $1/60 \div 1/100$ road bridge $1/30 \div 1/50$ railway bridge |
| | Tied arch more stiff than the deck | Lower deck | $1/4 \div 1/5 L$ $1/4 \div 1/6 L$ inclined hangers | $1/30 \div 150$ $1/80 \div 1/100$ |
| | The deck more stiff than the arch | Lower deck | $1/6 \div 1/7 L$ | $1/100 \div 1/120$ |
| Steel | Fixed and pinned at both ends | Upper deck | $1/7 \div 1/10 L$ | $1/40 \div 1/60$ |
| | Tied arch | Lower deck | $1/6 \div 1/9 L$ | $1/25 \div 1/40$ |
| Aluminium | The same as steel | | | |
| Glue-lam timber | All structural forms | | $1/7 \div 1/10 L$ | $1/30 \div 1/50$ |
| Composite polymer | To small population | | | |

3. CLASSIFICATION OF CONSTRUCTION TECHNOLOGY OF LARGE ARCH BRIDGES

Most concrete arches have been constructed with the concrete forms and in situ concreting being completely supported by falsework. They have also been constructed by means of tieback cables from a tower that is supported by cables anchored into the ground. Each tieback cable would support the forms for a segment length of concrete rib. For multiple arches, the tiebacks would support the forms and wet concrete in balanced cantilever segments off a tower erected on a common pier. Segmental concrete arches have been erected by cranes that are supported on the ground or on barges. They pick up a concrete segment and connect it to a previously erected segment. Another way of delivering and erecting the concrete segments is by means of a cableway spanning between tower bents.

Steel deck arches have also been erected in segment lengths by means of tieback cables. Another erection method is to have steel rib segments span the distance between temporary erection bents. For the usual tied-arch span the deck and steel tie can be erected on temporary erection bents. When this operation has been completed, the ribs of the arch, bracing, and hangers can be constructed directly off the deck. An alternative erection scheme that has been used is one in which the deck, steel ties, and ribs are erected simultaneously by means of tieback cables. A more spectacular erection scheme, that is economical when it can be used, involves constructing the tied-arch span on the shore or on

piles adjacent and parallel to the shore. When completed the tied arch is floated on barges to the bridge site and then pulled up vertically to its final position in the bridge. Some arches have had a rib erected on each shoreline in the vertical position as a column. When completed, the ribs are then rotated down to meet at the center between the shorelines.

Summing up, the construction methods of arch bridges can be as follows:

- cast-in-situ (reinforced concrete and post-tensioned structures),
- assembling on the scaffold (steel and precast concrete structure) on site,
- lifting of whole structure and placement on piers with/without temporary supports after assembling in factory or in construction site,
- launching with/without temporary supports along or across to longitudinal axis of the bridge,
- cantilever method with/without temporary pylons and cables,
- floating and lifting.

4. CAST-IN-SITU AND PRECAST ASSEMBLING OF THE CONCRETE ARCH BRIDGES WITH/WITHOUT TEMPORARY SUPPORTS

4.1. INTRODUCTION

Technologies used for erection of a concrete arch bridges can be divided generally in two main groups: cast-in-situ construction and precast construction (prefabrication). In basic terms, cast-in-situ construction describes a process whereby segments (or entire spans) are progressively cast on site in their final positions within the structure. By comparison, for precast construction, the segments are prefabricated at a casting plant – either on site or at a remote facility – then transported to the project site and erected as completed units in their final positions. Safety, serviceability, cost-effectiveness, aesthetics and particular technical issues are typically the controlling factors in the selection of the proper concrete bridge construction method [9]. There are not many concrete arch bridges built in Poland in recent 30 years. However two examples to illustrate the recent domestic achievement in both technologies have been chosen and presented below.

4. 2. THE CASTLE BRIDGE IN RZESZOW [8,14]

This is the five-span continuous structure with total length of 172.0 m and the total width of the deck 21.0 m [14] (Fig. 1). The superstructure is made up of three steel box-girders with the depth of 1.5 m and axial spacing of 6.4 m, composite with RC deck slab 0.25 m thick (Fig. 2). In the main spans the superstructure is supported on three reinforced concrete (RC) arches with 50.0 m axial length (Fig. 3a). The arches with the altering rectangular cross-section (2.5 x 2.5 m at base and 1.7 x 2.5 m at crown) are founded on concrete diaphragm walls. Each RC arch with the respective foundation diaphragms creates a rigid frame which highly influenced the structural conditions of the RC arch cross-section. Moreover, the street level on the bridge, the local terrain configuration as well as the hydrological requirements made the arches relatively flat ($f/l = 1/5.8$). These constraints caused the very dense reinforcement had to be used in the arches cross-section (Fig. 3b). It was the main reason for self-compacting concrete (SCC) application for arch construction with the total volume of about 900 m³ and with the standard compressive strength not less than 50 MPa. In those days (2002) it was one of the largest world structural applications of SCC for bridge structures. The formula of SCC to be applied in the bridge arches was prepared on the base of the comprehensive studies on the properties of respective mixtures [8].

The arches were cast on-site using timber formwork supported on steel scaffolding, which comprised two temporary supports founded in the riverbed and a steel gird made of I-rolled sections (Fig. 3c). The formwork and scaffolding were designed individually, which gave high flexibility to the design of the arches. The scaffolding was combined of standardized reusable steel sections that could be used over and over again. The individual timber formwork created the shape of the concrete arch section and enabled to construct the most slender and effective arch design. The arches were cast in a continuous way by means of standard concrete pumps, simultaneously from the both river banks, starting from the bottom and finishing at the arch key. Concreting of a single arch with the capacity of 290 m³ took from 18 to 22 hours. No vibration compacting was applied during concreting. When the operation was completed, the arch was covered with mats and traditionally cured for 7 days. Removing the formwork and scaffolding from beneath each arch 14 days after the concrete was poured, finished the arch construction. The individual steel scaffolding and timber formwork were used to construct the arches because they were flexible and cheap. The steel box superstructure was assembled by mobile cranes and connected to the arches in their crowns with special studs.

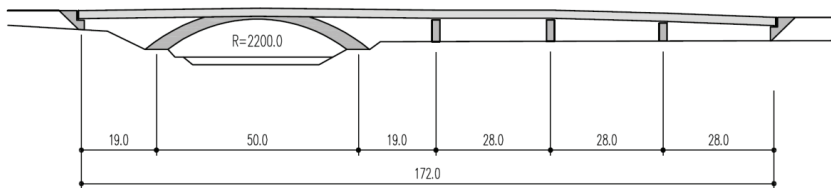


Fig. 1. The view side of the Castle Bridge in Rzeszow

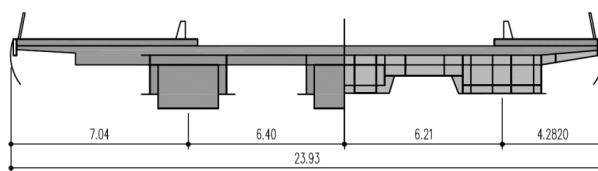


Fig. 2. The Cross section of the Castle Bridge in Rzeszow

a)



b)



c)



Fig. 3. Concrete arches of the Castle Bridge in Rzeszow: a) general view; b) dense reinforcement of arches; c) steel scaffolding and timber formwork of arches

4.3. VIADUCT IN MILOWKA ALONG S69 EXPRESSWAY [5]

In precast arch bridge construction, the individual components (arch segments) are manufactured off-site and assembled on-site. This method usually increases the arch durability, reduces on-site work and construction time, minimises environmental burdens and traffic disruption, and lowers life-cycle costs. Pre-casting gives the benefit of good control of the quality of construction, while the deck construction is simple and repetitive. Bridge superstructures made of precast arches are widely used nowadays. The only Polish example of a large arch bridge made of precast segments is the bridge in Milowka, located along the S69 expressway connecting the city of Bielsko - Biala and Silesia region with Slovakia [5]. The bridge with a total length of 663 m consists of nine concrete beam spans with a minimum length of 32.0 m (side spans), typical length of 41.0 m and three upper deck concrete arches with a span of 103.84 m (Fig. 4 and Fig. 6a). Maximum height of piers is 27 m and the deck width is 12.9 m (Fig. 5).

The concrete arches (two in each span spacing of 6.80 m) were erected using large size precast elements with a cross-section of 0.60 x 1.00 (1.40) m, supported during assembling on temporary supports (Fig. 6b). The supports were designed individually and built with steel tubes braced by cross-beams stiff enough to support the precast concrete segments of the arches, weighing up to 36 tons. On the top of each support the RC slabs were placed to brace them horizontally and to use as formwork for cast-in-situ joints. Each arch span consisted of $2 \times 2 \times 7 = 28$ precast segments. Due to heavy weight the precast elements were fabricated on site next to arch foundations. The segments were assembled by means of two mobile cranes in the direction from the foundations to the crown of the arch. After placing segments on supports the monolithic joints were cast along with the concrete spandrel columns supporting the deck. Concrete deck of the bridge was constructed using a movable scaffolding system (Fig. 6c).

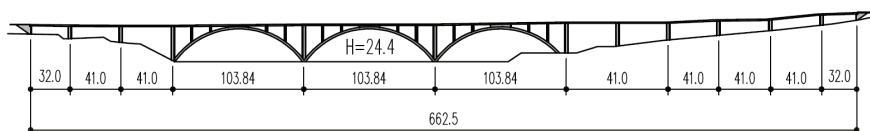


Fig. 4. General view of Milowka Viaduct

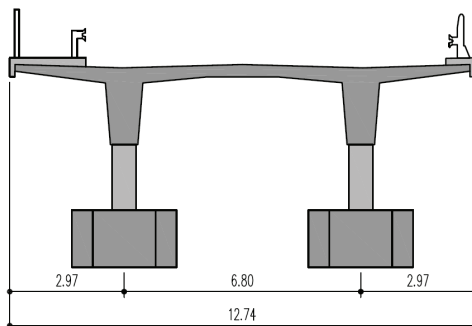


Fig. 5. Cross section of Milowka Viaduct

a)



b)



c)

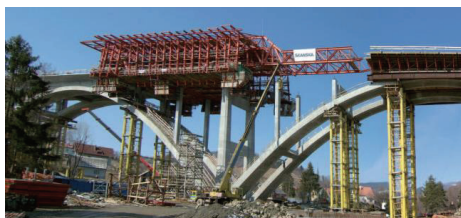


Fig. 6. Concrete arches of Milowka Viaduct a) general view; b) and c) steel scaffolding and timber formwork of arches

5. ASSEMBLY ON TEMPORARY SUPPORTS WITH LIFTING OF STEEL ARCH BRIDGES

5.1. INTRODUCTION

The choice of a construction method for a steel arch bridge is influenced mainly by the bridge location. Regarding steel arch bridges built recently in Poland, the principal methods of construction

are: construction with a mobile crane from the ground and/or the deck, placement of large steel segments with heavy lifting methods, construction by launching, and floating segment or an entire superstructure with a barge.

Construction with a mobile crane is an advantageous means of erecting the steel arch because it requires less equipment on site and a reduced amount of labour. Erection using cranes is considered the most cost effective erection method for the majority of steel structures. However, it does require good accessibility around the construction site. The erection may take place either with or without temporary supports. Due to the increasing capacity of lifting equipment, the current trend is to avoid the falsework which is generally expensive, while increasing the size of the steelwork pieces and making the maximum use of those parts of the superstructure already in place to support those that follow. The bending moments that can be resisted at the bases of the telescopic arms of mobile cranes currently used worldwide can be as high as 15,000 kNm, which means that, e.g. a weight of 100 tones can be carried at a distance of 15 m. If the arch spans are sufficiently short, and the size of the individual steelwork pieces allows, the temporary supports can be avoided.

However, if temporary supports are used, they may be either continuous or discrete. The evolution of heavy lifting equipment means that when temporary supports are needed, they tend to be a small number of discrete props rather than continuous falsework. An alternative method may be used if the deck of the bridge is sufficiently strong and stiff in bending, or perhaps it can be supported with temporary supports. To begin with, the deck is constructed either from the ground or launched. Once the deck is in place, it serves as a working platform for constructing the arches. Falsework towers are supported on the deck and allow relatively easy erection of the arches.

5.2. STEEL ARCH BRIDGE MA-37 ALONG A4 MOTORWAY OVER SAN RIVER [2]

This is an example of steel arch bridge construction with a mobile cranes on temporary supports [2]. It consists of two separate arch structures - one for each carriageway of the motorway. The bridge is a single - span network arch bridge with a span of 150.0 (Fig. 7). The deck is a steel grid of longitudinal beams and cross-beams composite with reinforced concrete deck slab, suspended to two arches by means of a net of diagonal hangers (Fig. 9a). Concrete end cross-beams were cast joined monolithically with massive bases of the steel arches (Fig. 8). The arch is tied by the 27L15.7 mm tendons located in the RC slab.

The steel grid was assembled using temporary supports founded in the river bed (Fig. 9b). Two mobile cranes were assembling the deck segments successively from both sides of the bridge. After placing

all segments on supports welding was used to assembly the deck. Finally the concrete slab was cast on the grid (still supported) creating a composite structure of the deck. The second stage of bridge construction comprised assembling of steel arches (Fig.9c). To facilitate arch assembling the outer auxiliary towers (four per each span) were constructed. The arches were assembled with three segments each, rested on auxiliary towers and joined together by welding. Finally, lateral bracing was constructed by welding steel pipes, followed by mounting and tensioning network cables.

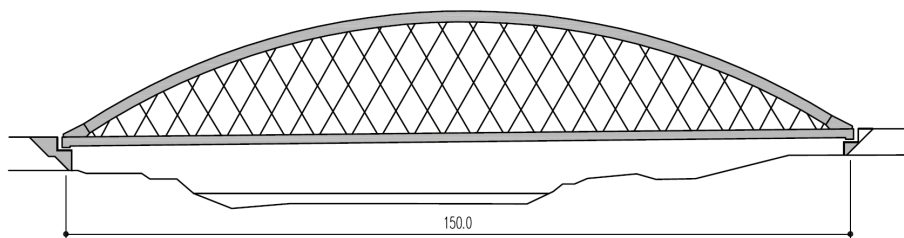


Fig. 7. View of the steel arch bridge M-37 along motorway over San River

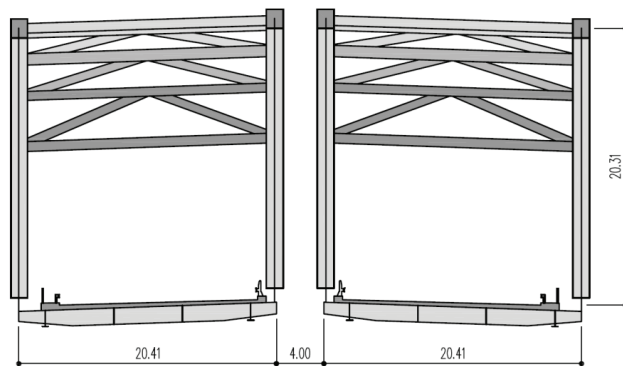


Fig. 8. . Cross section of the steel arch bridge M-37 along motorway over San River



Fig. 9. Bridge MA-37 along A4 motorway over the San River a) general view; b) steel scaffolding c) air view on the deck

5.3. STEEL ARCH VIADUCT ALONG SLOWACKIEGO STREET IN GDANSK [10]

Construction with a mobile crane and auxiliary supports is often combined with heavy lifting (HL) method of steelwork assembling. Heavy lifting (or strand jacking) is a hydraulic lifting technique especially developed for extremely heavy loads and usually applied for lifting of precast segmental superstructure members. Heavy lifting is not commonly used as an erection technique as it is best suited to large lifts that cannot be carried out by crane. The division of the structure into an erectable portion has to be influenced by the capabilities of the equipment. The technique provides a particularly timely and economic solution for projects based on modular construction methods and large, heavy, pre-fabricated elements. In Poland HL is perhaps most commonly used for lifting long midspan river sections from a barge. However, it is suited to other cases such as the central section of the arches, which are usually lifted onto the deck and transported into position beneath the jacking towers. Such kind of erection examples regarding to large arch bridges have been presented below.

The first example combining auxiliary supports and HL for steel arch bridge assembling is the viaduct built in Gdańsk along the Slowackiego Street, in the direct vicinity of the Euro 2012 PGE Arena stadium [10]. The viaduct has the static scheme of a 4-span continuous beam, while the longest span is suspended to the steel arch. The span lengths are: 40.0 + 120.0 + 56.0 + 44.0 m and the total length of the viaduct is 262.0 m. The superstructure is a multi-chambered concrete box, post-tensioned with internal and external cables, with slab overhangs supported with steel tubular struts. The deck width varies from 22.72 to 30.60 m. The longest span, crossing railroad tracks, is a tied arch with a length of 120 m (Fig. 10 and Fig. 12a). The box girder is suspended along its centre web axis to the arch. The arch consists of two 1.50 m diameter steel tubes, braced transversally with 0.80 m diameter steel tubes, forming together a spatial structure (Fig. 11). The concrete deck is suspended centrally by means of vertical steel rods.

The concrete superstructure was built in a classical way with concrete casting in a system formwork rested on temporary supports made of steel pipes. The tubular arch was assembled on the deck with the help of a mobile crane with 100 ton capacity (Fig. 12b). Three large-size segments (two side and one central), with the approximate length of 48 m, were mounted by welding from 12 m sections. The side segments were assembled by lifting with a mobile crane followed by supporting on auxiliary towers (Fig. 2c). Then side segments were fixed to the concrete arch bases formed in the concrete deck above span supports. Subsequently, the 48 m long central part, having been integrated on the deck slab, was lifted with the HL system with hydraulic jacks. Finally, all arch segments were welded on site, followed by mounting and tensioning the tie and vertical hangers.

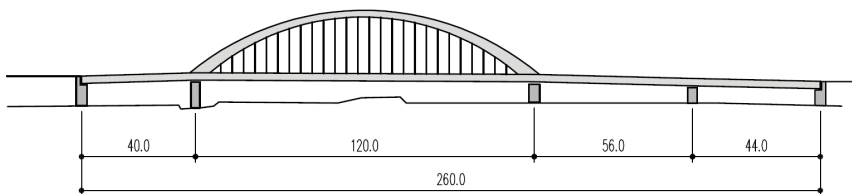


Fig. 10. View of the viaduct along Slowackiego Street in Gdansk

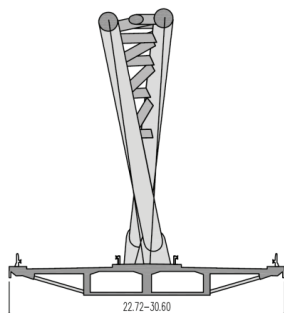
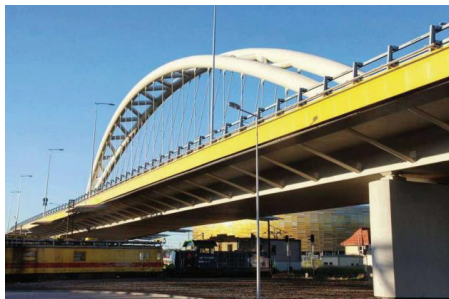


Fig. 11. Cross section of the viaduct along Slowackiego Street in Gdansk

a)



b)



c)



Fig. 12. Viaduct along Slowackiego Street in Gdansk
 a) general view; b) and c) steel temporary supports

5.4. STEEL ARCH BRIDGE OVER THE VISTULA RIVER IN PULAWY [1]

Similar assembling techniques, i.e. auxiliary supports and HL have been applied in construction of the second longest arch bridge, built recently in Poland. The bridge over the Vistula River in Pulawy is a continuous 14-span structure with spans of $44.0 + 3 \times 56.0 + 6 \times 64.0 + 80.0 + 212.0 + 80.0 +$

44.0 m, with the longest arch span crossing the riverbed (Fig. 13 and Fig. 15a). The total length of the bridge is 1038 m. Two inclined steel arches have a rhomboidal box cross-section, varying from 2.5×3.0 m over the support to 2.5×2.0 m in the crown. The arches are braced by steel box struts and tied by longitudinal beams, consist of two tandem plate girders of a constant height of 3.0 m (Fig. 14). The tie beams are braced by cross-beams with regular spacing of 4.0 m. The reinforced concrete deck slab has a thickness of 0.25 m and is made composite with an aforementioned steel grid (Fig. 15b). The deck is suspended by 28 vertical hangers to the arches.

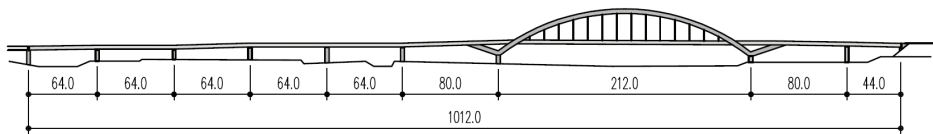


Fig. 13. View of the steel arch bridge across the Vistula river in Pulawy

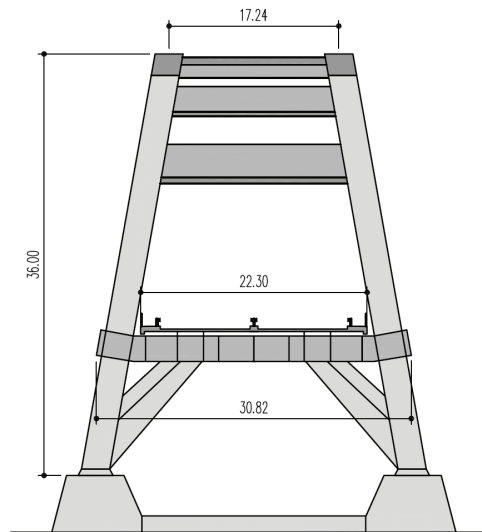


Fig. 14. Cross-section of the steel arch bridge across the Vistula river in Pulawy

a)



b)



c)



Fig. 15. Steel arch bridge over the Vistula River in Pulawy a) general view; b) placement of the deck c) steel temporary supports for erection of arches

Assembly of the deck in the arch span started with the construction of two auxiliary supports situated in the river bed. Simultaneously, the starting deck segments were placed on the bridge supports using a floating crane. The remaining part of the deck comprised three large segments: two 42 m long side segments with the weight of 380 tons and the center one with the length of 64 m and the weight of 555 tons. These segments were mounted on the construction site located on the river side and then floated on barges to the right position and lifted from the barges using the heavy lifting method with hydraulic jacks. Subsequently, all segments were joined together by welding to finish the steel deck construction. Finally, the track was placed on longitudinal tied beams to facilitate subsequent arch assembling.

The arches were divided for assembling into three large segments each, which were mounted in the same place as the former deck segments. Four auxiliary towers with hydraulic jacks on the top were constructed on the deck to lift arch segments during assembling and to support them for welding. Each arch segment was then longitudinally launched on trolleys along the tie beams of the deck to the right position (Fig. 15c). The total weight of the steel segments placed on the deck exceeded 2700

tons. Side segments were then lifted by HL, rotated and rested on towers, while the center segment was vertically lifted into the final position by HL, rested on towers and joined together with the side ones by welding. After connecting the segments to unify the arches, the tubular bracing struts were mounted. Finally, the auxiliary towers were removed from the deck, and the vertical hangers were installed and tensioned. After hangers tensioning the deck was lifted from the auxiliary supports located in the river bed. Then the concrete deck slab was cast and deck equipment was placed on it.

6. LAUNCHING

6.1. INTRODUCTION

The method of launching the steelwork is adopted when lifting equipment cannot access the whole length of the bridge, or when the height of the bridge becomes too big for lifting with cranes located on the ground. The launching method has been widely applied to tied-arch steel spans worldwide. The launching method of a steel arch bridge construction is about assembling the elements of a structure in an area that is in line with the bridge axis and located at the approach road. The superstructure is completely assembled, including cross frames and bracing, prior to launching operations. As the elements are joined together piece by piece, the arch structure is pulled or pushed, in stages, into its final position. Launching has the advantage of allowing all the steelwork elements to be assembled on the ground in the construction site (assembly area), which means that work can be carried out in more suitable conditions than may be the case with alternative construction methods. This is particularly important regarding welding operations. Three examples of the application of launching for arch bridge construction have been presented as follows.

6.2. THE KOTLARSKI BRIDGE OVER THE VISTULA RIVER IN CRACOW

[3, 4]

This bridge is 257.74 m long and consists of two approach viaducts and the main arch span with the length of 166 m. The arch superstructure is a spatial, simply supported, steel structure, composed of four (two internal and two external) “lens” arch girders and an orthotropic deck (Fig. 16, Fig. 17, Fig. 18a). Lens arch girders consist of upper parabolic arches and bottom circular arches, with different elevations for the internal and external ones. Effective distances between the arch centre lines are 18.01 m and 14.02 m respectively, so with a total span of the arch that gives the slenderness ratio L/h equal to 9.2 and 11.8. The total width of the bridge is 36.84 m. Main beams are suspended to upper

arches by means of hangers and with bottom arches with I-shape pillars. The deck was constructed as a steel orthotropic plate composed of a sheet plate, longitudinal trapezoidal ribs and transversal I-beams, supported on longitudinal main beams placed at the arch girders' plane.

The bridge erection was realized into two stages. In the first stage the bottom arches and deck were assembled together on the construction site in line with the bridge axis and located at the approach road. The assembly area was located on the river bank and enabled the assembling of the 50.5 m long segment (maximum). The bottom part of the superstructure was than launched "stage by stage" onto four auxiliary supports built in the riverbed to its final position (Fig. 18b). A short 5 m long avanback (nose) was applied to facilitate launching. The location of the auxiliary supports had to guarantee undisturbed navigation on the Vistula River. The arrangement of auxiliary supports in each launching phase enabled the outer arches to rest on the supports at the end of each launching phase. A slide bearing were positioned below the internal arches. Five phases of bridge launching were realized, the first launching phase assumed 50.5 m.

In the second stage, after launching the bottom part of the superstructure into its final position, the erection of upper arches, bracing and hangers assembling was completed. These elements were lifted from the deck level to its final position with mobile cranes (Fig. 18c). The common scaffolding system was put on the deck and used to support all pieces of a steelwork to be mounted. After welding together all elements, the whole superstructure was released from the auxiliary supports by lifting, and lowered onto the right bank piers. After the superstructure had been lowered to its final position, the auxiliary supports were removed from the riverbed. The final regulation of vertical hangers was then completed.

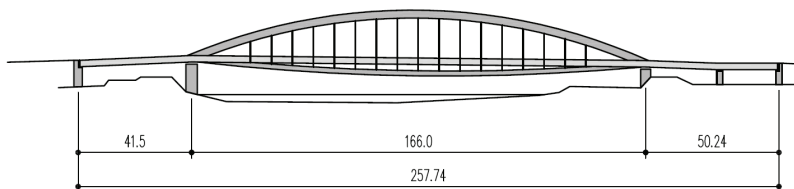


Fig. 16. General view of the Kotlarski bridge over the Vistula river in Cracow

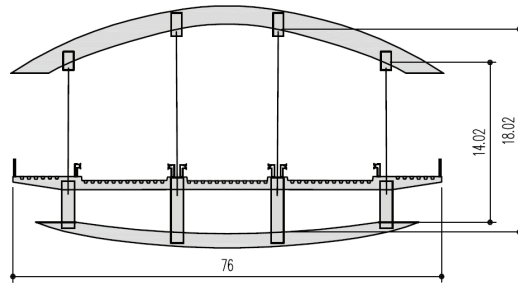


Fig. 17. Cross section of the Kotlarski bridge over the Vistula river in Cracow

a)



b)



c)



Fig. 18. Kotlarski steel arch bridge over the Vistula River in Cracow a) general view; b) construction of the deck c) erection of arches on steel temporary supports placed on the deck

6.3. BRIDGE OVER THE WARTA RIVER ALONG THE S3 EXPRESSWAY

[11]

The launching method has been also used as the construction method of the mentioned above bridge. It consists of two separate structures - one for each carriageway of the expressway. The each bridge consists of two parts, separated by an expansion joint: section I – the midstream part and section II – the approaching part over flooding area. The midstream section is a continuous, six-span composite structure, with a total length of 396.0 m (48.0+60.0+60.0+120.0+60.0+48.0). The longest span of two steel tied arches is 120.0 m. The total width of the superstructure structure is 14.40 m (Fig. 19a). The entire deck consists of two steel box girders made composite with the RC deck slab. The slender steel arches have a parabolic shape in the centre section (near the crown) and straight sections near the bases. Both steel arches with the box-section of 1.45 x 1.2 m are braced transversally by two „X” shaped steel tube bracing at portal parts of the structure and the RC cross-beams at the supports (Fig. 19c). In the arch span the deck is suspended to the arches by means of steel rods. The hangers are anchored in the parabolic section of the arches and have a fan arrangement radiating towards the deck. The entire arch span along with the respective approaching spans was assembled on the embankment in the riverside. Starting with the deck the subsequent steel elements of both arches with a length of approximately 30 m were successively positioned, mounted and welded together. After assembling of the arch span and two approaching spans at both sides of the arch, the launching begun. Construction technology assumed launching the whole steel structure of the bridge using an auxiliary support located in the riverbed (Fig. 19b). Moreover, an avanback (nose) was applied to facilitate launching. After the launching has been completed, the cable hangers were installed and adjusted by means of hydraulic jacks located on the auxiliary support in the mid-span, which allowed for lifting or lowering the deck. After installation and pre-tension of the hangers, the auxiliary support was removed. In the last construction stage the RC slab was cast on the entire steelwork followed by the installation of deck equipment and final hangers' adjusting

a)



b)



c)



Fig. 19. Bridge over the Warta River along the S3 expressway a) general view; b) erection of arches on steel temporary supports placed on the deck; c) side span assembled on the bank of river

7. FLOATING AND LIFTING

7.1. THE HORIZONTAL ROTATION LAUNCHING METHOD VIA FLOATATION ON BARGES

7.1.1. INTRODUCTION [6, 15]

This method provides the optimal urban bridge construction solution by reducing impact on traffic, improving safety, and optimal project budget and duration. This method includes building the bridge parallel to the obstacle being crossed (a river or a highway) and then rotating the superstructure into its final position. The method has been used recently for erection of single-span steel arch bridges, when span assembling on temporary supports, located on a highway or in a riverbed, is not

practicable. The superstructure is assembled on scaffolding situated on one bank (or alongside the highway) and launched by rotation pivoting about the one of superstructure's bearings into the bridge's final position. During this rotation process, one of the superstructure's ends rests on a special bearing, positioned directly on a bridge abutment (or on a fixed temporary support), and the second is rested on a movable support, such as a roller for land or on a barge for water. The rotation launching method has been used successfully in the last decade in over one hundred bridges in Austria, Canada, China, Germany, France, Italy, Japan, and the Republic of Slovakia and includes arch bridges [6, 15].

7.1.2. STEEL ARCH FOOTBRIDGE OVER THE VISTULA RIVER IN CRACOW [9]

Recently the rotation via floatation method has been used for construction of single-span steel arch pedestrian bridge connected two riverbanks in the historical city center, which strongly influenced both its architectural shape and the construction technology. The footbridge is a 148 m long tied arch steel structure with single span main tubular arch of circular cross section and twin suspended semi-circular orthotropic steel deck with timber planks. The superstructure has a geometry with an arch radius of $R=170$ m and the rise of 15.3 m. The superstructure is very slender with $H/L = 1/9.7$ (Fig. 20 and Fig. 21a). The main arch is made of two concentric steel tubes, with the outer one with diameter of 2020 mm and the inner one with diameter of 1620 mm. Inside the annulus between these steel tubes, self-compacting concrete was poured. The main arch has fixed ends in concrete abutments. The twin semi-circular orthotropic steel deck has a length of 137 m and a width of 3.4 m is suspended from the tubular steel arch with steel rope hangers in the "network" arrangement. Twin inclined hanger surfaces in a semi-circular shape in the network pattern plus a steel orthotropic deck create a very stiff triangulated structural system, which enhances the rigid body behavior of the superstructure. The orthotropic steel deck is supported with 508 mm diameter tubular crossbeams, suspended directly from the tubular arch. There are two external ties made of two 19×15.7 mm cables which are situated under each deck part. The ties are anchored in the end crossbeams and connected to concrete abutments with special steel brackets.

The Vistula River had to remain open for navigation and the conventional traditional method of construction on temporary supports founded in the riverbed were challenged by the river administration. Therefore, it was decided to site assemble the entire superstructure on the right bank of the river and to launch it by rotation as a rigid body by means of a floating support into its final position on the left bank or south bank abutment. The superstructure site assembly location was chosen along the right river bank, and the construction site were adjusted to aid in the rotation via floatation of the superstructure (Fig. 21c). After assembling the entire superstructure by means of

scaffolding and two auxiliary towers located on the ground and the deck, respectively, the inclined vertical hangers and the horizontal wire rope tie were partially pre-tensioned following the removal of scaffolding. Thus superstructure was ready as a rigid body for rotation. The superstructure would be a tied arch during the erection and floatation process. After the erection by floatation the superstructure would be converted to a fixed arch with steel tube rigidly connected or fixed to the reinforced concrete abutments.

Superstructure assembly made it possible to create a very rigid body spatial structure. However, construction of additional temporary supporting structures was also needed for launching to ensure stability and safety of the span during rotation. The special track structure for launching was erected on the right bank. The floating support consisted of a large and small barge (large was 70 m x 10 m in plan) joined together by means of a grillage comprised of I-beams and steel wire ropes, and equipped with the rotation table at the joint between barges.

The rotation launching via floatation of the superstructure proceeded as follows (Fig. 21b):

- lifting of the south superstructure end on the rotation table support to the elevation required for launching;
- sliding the left-side superstructure end on the track by means of jacking towards the floating support or barges;
- rotation of the entire superstructure approximately an angle of 90° into the left bank abutment; via the rotation tables, the two barges were always positioned parallel to the current of the river; tugboats assisted in aligning the barges;
- lowering the superstructure after launching via floatation to the required final elevation of the superstructure and resting it on the temporary supports located on both banks;
- connecting the superstructure with steel elements fixed or embedded in concrete abutments;
- coupling the tie cables with turnbuckles to their short embedded parts cast into reinforced concrete abutments along with the final adjustment of tension force.

The rotation via floatation was realized by means of four wire ropes and hand winches with the assistance of two tugboats or pushers, in front (upstream and downstream) of and behind the two barges, which enabled full or 100% control over the floatation operation. The speed of rotation was about 2 m per minute (along the radius) and the whole launching operation lasted only about 6 hours. After the span was connected to the abutments, equipment installation completed the footbridge construction. The final tuning of inclined wired rope hangers in the “network” pattern was the last operation performed before opening.

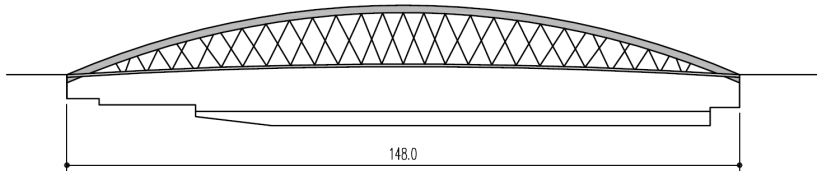


Fig. 20. "Bernatka" pedestrian bridge over Vistula River in Cracow

a)



b)



c)



Fig. 21. Bernatka steel arch footbridge over the Vistula River in Cracow a) general view; b) construction of the structure on the riverbank c) floating of the bridge

7.2. FLOATING AND LIFTING

7.2.1. INTRODUCTION

The complete tied arch bridge or its sub-structures weighing hundreds of tonnes may be transported into their final position by floating. The most commonly used method, when the bridge crosses a navigable stretch of water, is the placement of the steel arch structure on barges for floating. If the

bridge is assembled in an area further away from its final position, then the complete structure can be placed on barges to be transported from the assembly area to its final location. Tied arch bridges lend themselves to placement of the complete bridge because their support reactions are uniquely vertical. A temporary tie must be used during erection to stabilize arches that will not be tied in their final state. Preassembly is only possible when there is sufficient space to construct the arches on the banks. In urban environments, therefore, preassembly of the complete bridge is often difficult. The bridge is commonly erected on one of the banks, parallel with the bank edge. This method is considered economical because the work associated with erection of the arch is carried out on the ground, giving easier access to the whole of the assembly area, with no need to use any special equipment.

7.2.2. “NETWORK” ARCH BRIDGE OVER THE DZIWNA RIVER TO CONNECT WOLIN ISLAND WITH THE MAINLAND [18]

The total length of the structure is 1096 m. This multi-span bridge consists of three types of structures divided into five parts connected with expansion joints. The main span over a river is a steel tied network arch 165 m long and the approaching multi-span steel-concrete composite and pre-stressed concrete structures are located on both sides of the main span (Fig. 22 and Fig. 24a). The arch span consists of two inclined steel box arches with a rise of 24 m (slenderness $H/L = 1:7$) and a composite deck. The arches are steel box girders with a constant rectangular cross-section of 1.00×1.80 m and are braced by seven tubular struts with a diameter of 1.22 m. The steel deck grid comprised two outside girders, one central stringer, and traverse cross-beams with cantilevers beyond the outline of the bridge to attach the hangers (Fig. 23). The grid is covered by the RC slab made compositely with steel grid beams. The thrust of the arch is transferred by a tie made of six external cables of size 37L15 (three per girder), anchored in concrete bases of the arches. The pre-stressing force is greater than the thrust of the arch and causes pre-stressing of the reinforced concrete deck slab. The diagonal hangers in the network arrangement are made of the closed ropes, which constitute the deck suspension.

The steelwork of the arch bridge was manufactured in Szczecin shipyard remote from the construction site about 100 km. The arches were manufactured in three segments comprising a pair of box arch sections each: the central segment with the length of 68.5 m and the weight of 178 tons and two side mirror segments with the length of 50.4 m and the weight of 155 tons. Each segment was placed than on the barge and was floated to the construction site. In the same time, in the riverbed, exactly in the bridge axis and in 1/3 span distance, two 37 m high auxiliary towers were erected to facilitate the arch segments assembling on site (Fig. 24b and Fig. 24c). The barges floated with the segments

exactly along the bridge axis and the HL was used to lift segments to the right position. After lifting and temporarily supporting on towers the segments were mounted together by welding.

The deck grid sections up to 24 m in length were manufactured and transported to the construction site in the same manner. The successive assembling of deck segments from one support toward the opposite one was realized with lifting them from barges and welding at the deck level. Simultaneously, the suspension was installed, attaching hangers to arches and deck cantilevers in the network arrangement (Fig. 24d). When the whole steelwork of the arch span was completed, the span was pre-tensioned with a tie and casting of the RC slab begun, followed by the installation of bridge equipment. The concrete for the deck slab was pumped from a barge in the design sequence with partial stressing the tie cables. Finally, the adjusting of the tie and hangers was carried out.

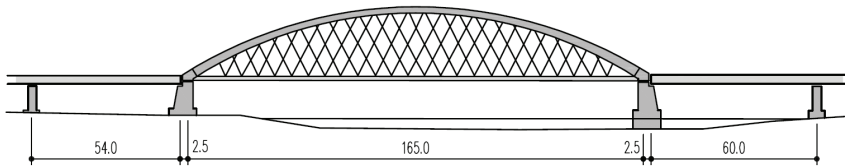


Fig. 22. View of the Wolin Island – Mainland bridge over the Dziwna river

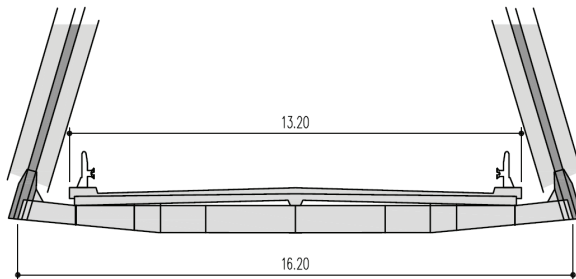


Fig. 23. Cross section of the Wolin Island – Mainland bridge over the Dziwna river



Fig. 24. Steel arch bridge over the Dziwna River in Wolin a) general view; b) Transportation of the part of the arch on the barge c) assembling of the arch d) construction of the deck

7.2.3. STEEL ARCH BRIDGE OVER THE VISTULA RIVER IN TORUN [13]

The floating of the entire arch span has been used in the construction of the longest Polish arch bridge, built over the Vistula River in Torun. The bridge with the total length of 1871,4 m consists of the following parts: right approaching flyovers with a length of 221.7 m + 279.5 m, two span arch bridge with a length of $2 \times 270,0 = 540,0$ and left approaching flyovers with a length of 435.3 m + 394.9 m (Fig. 25 and Fig. 27a). The total width of the deck carrying two carriageways and sidewalks is 24 m (Fig. 26). The main arch bridge is a half through fixed arch structure with two spans of 270.0 m. It is located over the mainstream of the Vistula River, thus the central support is situated on an artificial island in the centre of the riverbed. Steel arch girders with the hexagonal box section with dimension of 2.5 x 3.0 m, are inclined to the axis of the bridge and braced by six transverse struts. The arch

girders are equipped with the concrete bases to facilitate span support. There is no tie in the arch structure. The 3.0 m high steel deck comprised a grid with longitudinal beams and transverse cross-beams, suspended to the arches by vertical hangers. The deck grid is covered with a steel orthotropic plate consisting of closed ribs under the road pavement and open ribs under the sidewalks.

The construction of the arch bridge begun with the construction of foundations, including central support located on the artificial island in the mainstream, followed by the erection of concrete arch bases. Simultaneously, on the construction site located on the river bank the assembly of arch segments took place to prepare each arch span possible to be safely transported on barges to the bridge site (Fig. 27b). The entire arch (each of the two) was divided into two segments, which were assembled from the sections with a length of approximately 10 m. After the segments (half-arches) had been merged, they were launched transversally on two barges moored to the river bank. Two auxiliary towers were installed on barges to lift two segments of the arch span to the right level, to joint them by welding and to brace the entire floating system (arch, towers and barges) by rod stays for safe transportation (Fig. 27c). Floating, i.e. water transport of the whole system with steel arch of 3000 tons in weight, was the most demanding phase of bridge erection. Two mooring tugboats insured the floating operation. The floating system were aligned in the bridge longitudinal axis to be connected by welding to steel end sections encased in concrete support bases. Finally, the arch was fixed in the concrete support bases. The same construction sequence was repeated for the second arch. After fixing the arches had been realized, the assembly of 30 m long deck segments of the full cross-section of the bridge deck was performed. The deck segments were lifted from barges and, after hangers' adjustment, welded to predecessors in the direction from the supports towards the mid-span.

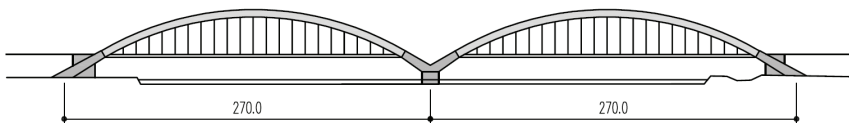


Fig. 25. View of the steel arch bridge over the Vistula river in Torun

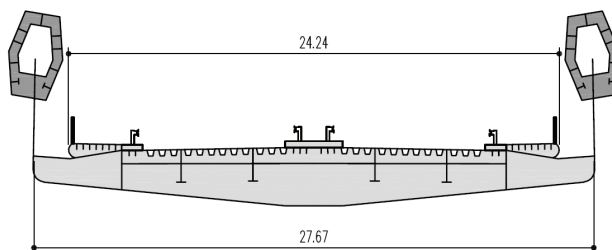


Fig. 26. Cross section of the steel arch bridge over the Vistula river in Torun

a)



b)



c)



Fig. 27. Steel arch bridge over the Vistula River in Torun a) general view; b) Transportation of the part of the arch on the barge c) fixing of the arch into concrete piers

7.2.4. STEEL ARCH BRIDGE OVER THE DEAD VISTULA RIVER IN GDANSK [17]

The railway steel arch bridge over the Dead Vistula River in Gdansk (Fig. 28 and Fig. 29). with the total length of 124,0 m is a tied structure supported on two abutments. It consists of three box girders

(ties) and three arches. Vertical hangers are located is spacing of 7,75 m. The arches are braced by five box struts. Total width of the structure is 15,0 m. The deck is a grid with concrete slab.

The Vistula River had to remain open for navigation and the conventional traditional method of construction on temporary supports founded in the riverbed was impossible to realize. Also assembling of structure on the bank of the river because of lack of space. Therefore, it was decided to assemble the entire superstructure in the fabrication factory (shipyard) about 30 km from the construction site. Integration of whole structure was done using stationary and mobile cranes. All elements were placed of temporary supports and mounted together to reach final geometry of the superstructure. The arches were divided into three segments (Fig. 30a). All of them were braced and lie horizontally on deck girders. Then, the whole structure was moved transversally on the pontoon (Fig. 30b). The uniform distribution of loads was controlled with the system of ballast tanks. The process of fulfilling and dewatering of the pontoon was crucial during travel under the neighbouring cable-stayed bridge. Finally, the pontoon was moored to the bank between cable-stayed bridge and old railway bridge which will be replaced by new one (Fig. 30c and Fig. 30d).

The next step was assembling of arches to the final shape which was done using mobile crane standing on the bank. At first the border parts of arches were lifted up and then the middle part was lifted and joined with the border elements. To put whole superstructure on the abutments two additional pontoons were applied. They were placed under the end of the structure and positioned to support it exactly in points of support on bearings. Those side pontoons were put out and middle pontoon was plunged. On this middle pontoon temporary supports were installed exactly under arch stiffeners. Those floating supports (three pontoons) were rotated into final position of the bridge and in the last step putting up the middle pontoon and putting down the side pontoons the bridge reached final position. Then hangers were installed, stretched and tuned.

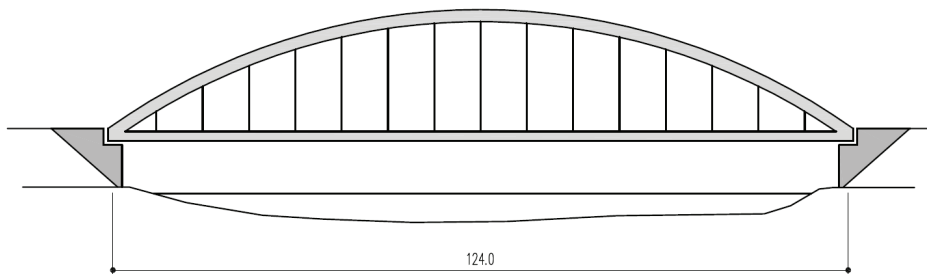


Fig. 28. Steel arch bridge over the Dead Vistula River in Gdansk

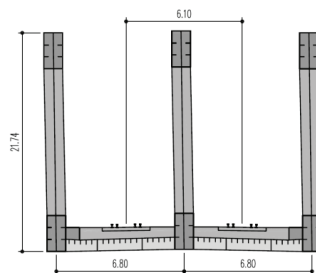
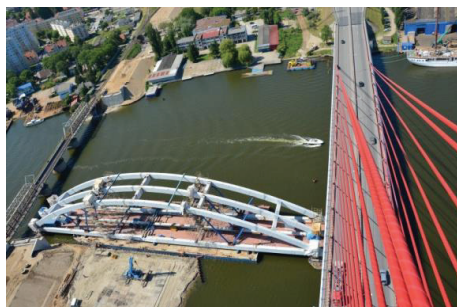


Fig. 29. Cross section of the steel bridge over the Dead Vistula River in Gdansk

a)



b)



c)



d)



Fig. 30. Steel arch bridge over the Dead Vistula River in Gdansk a) arch divided on three segments; b) superstructure placed on the pontoon; c and d) Transportation of the superstructure on the barge

8. CONCLUSIONS AND DIRECTIONS OF DEVELOPMENT

Two thousand years of existence of arch bridges shows that they are natural, nice, durable and structurally efficient structures [16]. These structures develop further and it can be expected new

solutions. The most important tendency is “mixing” of different materials – steel and concrete especially, but glue-lam timber and composite polymers looks good. Taking into account also the development of design methods we will see also development of new construction technologies or improvement of used now.

The realization of arch bridge in Poland has been dramatically increased in the last decades in favour of other bridge structures. The reason for such tendency is rather unexpected, because during the erection process the arch needs a provisional formwork to be sustained, which increases consistently the construction expenses and the need for labour. However, this is particularly true for small and medium spans, where the beam solution (whether continuous or simply supported) represent a simple and economic alternative. Considering that small and medium spans represent the vast majority of the bridges dislocated on the Polish territory, it is mandatory for a good designer to consider a structural solution which is at the same time economical and well inserted in the environment. In order to be competitive again, the arch solution needs to be reconsidered during its construction process reducing the onerous continuous formwork with the help of precast elements and new high strength materials.

The construction problem of an arch bridge is that it presents different static scheme that between construction phases and final use. The research for innovative construction techniques and the careful study of the structural behavior during the erecting stages permitted to the arch solution to be competitive again, after some decades of small use in Poland, mainly due to economic reasons. Therefore, a careful research of innovative construction techniques and a depth study of the behavior in the erection phases of assembly allow to bring back the arch bridge solution into competitive for the construction of large arch bridges. The arch architectural elegance, with a change of static schemes so extraordinarily between the construction and the service phases, allows to get in symbiotic harmony with the surrounding environment through its architectural features, emphasizing the poetic of the arch shape in engineering technology lecture key.

REFERENCES

1. Krysiak L., Pawelski S. The construction of the road bridge over Vistula in Pulawy (Budowa mostu drogowego przez rzekę Wisłę w Puławach). *Inżynieria i Budownictwo*, Vol. 62, No. 11, 2006, pp. 633-635.
2. Kulawik A., Kaczmarek A., Srokol S., Radziecki A. The motorway bridge over San River (Autostradowy most przez rzekę San). *Inżynieria i Budownictwo*, Vol.69, No.2, 2013, pp. 63-66.
3. Majcherczyk B. Kotlarski Bridge, Cracow, Poland. *Structural Engineering International*, Vol. 12, No. 3, 2002, pp. 163-165.
4. Majcherczyk B., Mendera Z., Piłujski B. The Kotlarski Bridge in Cracow – the longest arch bridge in Poland (Most Kotlarski w Krakowie – najdluzszy most lukowy w Polsce). *Inżynieria i Budownictwo*, Vol..., No. 3-4, 2002, pp. 125-130.

5. Marcinków E., Tatara J. Construction technology of the arch part of Miłowka flyover along S-69 expressway (Technologia budowy części łukowej estakady w Miłowce w ciągu drogi ekspresowej S-69). *Inżynieria i Budownictwo*, Vol. 62, No. 7-8, 2006, pp.408-411.
6. Mou T., Liang J., Fan B., Xie B. Development of the combination of vertical and horizontal swing techniques for the Dongping Bridge in Foshan. *Proc. 6th Int. Conf. "ARCH'10"*, Fuzhou University, China, 2010, pp. 797-807.
7. Radić J., Savor Z., Kušter Marić M.. Aesthetics of contemporary arch bridges. *Proceedings of the 8th International Conference on Arch Bridges - ARCH 2016 - Arch Bridges in Culture. Volume 1*; Wrocław, Poland, October 2016, pp. 19-34.
8. Radomski W. The first Polish application of self-compacting concrete in bridge construction. (Pierwsze w Polsce zastosowanie betonu samozagęszczzonego w konstrukcji mostu). *Inżynieria i Budownictwo*, nr 2/2003.
9. Siwowski T., Wysocki A., Horizontal Rotation via Floatation as an Accelerated Bridge Construction for Long-Span Footbridge Erection: Case Study. *Journal of Bridge Engineering ASCE*, Volume 20, Issue 4, 2015, pp. 05014014-1-9.
10. Topolewicz, K., Galewski, T. Construction of the WD-1 viaduct along the Słowackiego Route – section III in Gdańsk (Budowa wiaduktu WD-1 w ciągu Trasy Słowackiego - odcinek III w Gdańsku). *Mosty* 1/2013: 39-43.
11. Topolewicz K. Arch bridge over the Warta River in Gorzów Wielkopolski (Łukowy most przez Wartę w Gorzowie Wielkopolskim). *Proc. of Symposium Wrocławskie Dni Mostowe „Mosty stalowe. Projektowanie, technologie budowy, badania, utrzymanie”*, Wrocław University of Technology, 27-28 November 2008, pp. 163-170.
12. Wai-Fah Chen, Lian Duan. *Bridge Engineering Handbook: Volume 1*. CRC Press, 1999.
13. Wąchalcki K., Cywiński Z. Die neue Straßenbrücke in Toruń, Polen –Teil 1: Planung und Bau. *Stahlbau*, Vol.84, No.4, 2015, pp. 267–274.
14. Wolan Z., Wyszynski W. Construction of the Castle Bridge over Wislok river in Rzeszow (Budowa mostu Zamkowego przez rzekę Wisłok w Rzeszowie). *Inżynieria i Budownictwo*, Vol.58, No.6, 2002, pp.302-303.
15. Zhang J., El-Diraby T. Constructability analysis of the bridge superstructure rotation construction method in China.” *J. Con. Eng. Mngt.*, 132(4), 2006, pp.353–362.
16. Zobel H.: Mosty Łukowe. *Proc. of Symposium Wrocławskie Dni Mostowe „Mosty a Środowisko”*, Wrocław University of Technology, 28-29 November 2019, pp. 109-149.
17. Żółtowski P., Drachal R., Mikucki A., Bartoszewski B. New railway bridge over the Dead Vistula River in Gdansk – fabrication and assembling of the superstructure (Nowy most kolejowy przez Martwą Wisłę w Gdańsku – wytworzenie i montaż w ustroju nośnym). *Proc. of Symposium Wrocławskie Dni Mostowe „Mosty łukowe. Dzieła kultury. Projektowanie, budowa, utrzymanie”*, Wrocław University of Technology, 26-27 November 2015, pp. 277-283.
18. Żółtowski K.: Bogenbrücke über den Fluß Dziwna in Wolin – Entwurf und Realisierung. *Stahlbau*, Vol. 74, Issue 9, 2005, pp. 685-690.

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Rys. 2. Przekrój poprzeczny mostu Zamkowego w Rzeszowie

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Rys. 11. Przekrój poprzeczny wiaduktu wzdłuż ul. Słowackiego w Gdańsku

Fig. 12. Viaduct along Slowackiego Street in Gdansk

Rys. 12. Wiadukt wzdłuż ul. Słowackiego w Gdańsku

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Rys. 13. Widok stalowego mostu łukowego przez rzeką Wisła w puławach

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Rys. 14. Przekrój poprzeczny mostu łukowego przez rzeką Wisła w puławach

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OSTATNIO WYBUDOWANE MOSTY ŁUKOWE DUŻYCH ROZPIĘTOŚCI – PRZEGLĄD TECHNOLOGII WYKONANIA

Słowa kluczowe: most, wiadukt, most łukowy, technologie wykonania

STRESZCZENIE

Mosty łukowe są budowane od więcej niż dwóch tysięcy lat. W Europie ten typ konstrukcji jako pierwsi zastosowali Rzymianie. Niezależnie od nich mosty łukowe zaczęli w tym samym czasie budować Chińczycy. Materiałem konstrukcyjnym aż do epoki Renesansu był kamień (granit, piaskowiec, marmur). Mosty kamienne były budowane jeszcze w XIX wieku, a nawet są budowane jeszcze obecnie, choć sporadycznie. Jeszcze w Średniowieczu pojawiły się konstrukcje ceglane, które stopniowo zastępowały kamień, ale ich rozkwit nastąpił wraz z budową linii kolejowych.

Koniec XVIII wieku to początek budowy mostów stalowych, najpierw żeliwnych, a od lat 20-tych XIX wieku wykonywanych ze stali zgrzewanej. W latach 50-tych tego wieku opanowano produkcję stali zlewnej, która jest produkowana do dzisiaj, tyle, że zdecydowanie o innych właściwościach fizyko – mechanicznych. Koniec XIX wieku to z kolei początek budowy konstrukcji betonowych i żelbetowych.

Wiek XX przyniósł rozwój nowych materiałów, co znalazło także swój wyraz w projektowaniu i budowie mostów łukowych. Jeszcze przed II wojną światową pojawiły się mosty łukowe z elementami sprężonymi oraz mosty aluminiowe. Mosty z drewna klejonego to już lata 50-te XX wieku, a od 1982 roku rozpoczęto stosowanie kompozytów polimerowych jako materiału konstrukcyjnego.

Także wykorzystywane od dawna materiały takie jak stal i beton modyfikowano, co zaowocowało budową mostów łukowych ze stali nierdzewnej. Połączono również oba wyżej wymienione materiały dając możliwość budowy konstrukcji hybrydowych jak np. stalowych mostów łukowych z elementów zamkniętych wypełnionych betonem. Od pewnego czasu standardem stało się łączenie różnych materiałów w różnych elementach konstrukcji np. łuk stalowy z pomostem kompozytowym czy łuk drewniany z pomostem typu drewno – beton.

Jest wiele kryteriów klasyfikacji mostów łukowych. Kryterium materiałowe, użytkowe a także rodzaj przeszkody komunikacyjnej są najprostsze i najbardziej oczywiste nawet nie dla inżyniera. Natomiast z punktu widzenia projektanta i wykonawcy kluczową rolę odgrywa schemat statyczny (bezprzegubowy, dwuprzegubowy czy trójprzegubowy) co determinuje sposób przenoszenia siły rozporowej do gruntu albo bezpośrednio do gruntu (tzw. łuk rozporowy) albo za pośrednictwem klasycznych podpór mostowych (tzw. łuk ze ściągiem). Istotnym kryterium jest także stosunek sztywności łuku do sztywności pomostu.

Przekazanie sił z pomostu na łuk w konstrukcjach łukowych z „jazdą pośrednią” i z „jazdą dołem” wymaga zastosowania elementów łącznikowych, pracujących jako rozciągane. Nazwą powszechnie używaną są wieszaki. Wykonanie wieszaków wymaga zastosowania elementów o dużej wytrzymałości na rozciąganie oraz odpowiedniego połączenia ich z łukiem oraz pomostem obiektu.

Współczesne mosty łukowe zazwyczaj wykorzystują wieszaki wykonane jako prętowe, linowe (z lin zamkniętych lub wielosplotowych) oraz z kształtowników stalowych. Znane są także obiekty wyposażone wieszaki żelbetowe oraz sprężone. Wykonano także eksperymentalne obiekty z wieszakami z materiałów kompozytowych.

Wymienione wyżej uwarunkowania, a także inne tu nie wspomniane determinują wybór metody budowy. Technologie budowy mostów łukowych nie różnią się istotnie od stosowanych przy innych typach mostów. Można wymienić następujące najczęściej stosowane:

- montaż dźwigiem całej konstrukcji scalonej wcześniej na placu budowy,
- montaż na rusztowaniach,
- nasuwanie z lub bez tymczasowych podpór pośrednich (podłużnie lub poprzecznie do osi mostu),
- metoda wspornikowa (nawisowa) z lub bez wspomagania odciągami,
- montaż z użyciem berek.

W przypadku konstrukcji betonowych (dźwigarów, elementów pomostu) bardzo istotną sprawą jest zaprojektowanie i zrealizowanie procesu betonowania. Jest on kluczowy z punktu widzenia odkształceń łuku oraz elementów pomostu, w szczególności płyty pomostu.

Decydującymi czynnikami są:

- kolejność betonowania,
- długość betonowanych fragmentów,
- grubość betonowanych warstw,
- liczba i wielkość przerw technologicznych.

Z kolei te czynniki są ściśle powiązane z recepturą betonu, która w decydujący sposób wpływa na szybkość wiązania betonu i co za tym idzie czas uzyskiwania potrzebnej wytrzymałości, a to w konsekwencji przekłada się na czas realizacji inwestycji.

Osobnym zagadnieniem jest montaż wieszaków (słupków, ścian). W tradycyjnych konstrukcjach łukowych, jak już to wspomniano wyżej były to pręty obetonowane w betonowych mostach łukowych i składające się z kształtowników w przypadku mostów stalowych. Były one łączone „na sztywno” z konstrukcją łuków i pomostem. Nie było możliwości ich

naciągu (kontrolowanego wprowadzenia odpowiedniej wartości sił). W chwili obecnej praktycznie budowniczo wie odeszli od takich konstrukcji i stosuje się albo pręty sprężające albo ciężna wiotkie (kable sprężające). W konsekwencji, w zależności od przyjętego systemu mocowania stosuje się zakotwienia bierne lub czynne. W pierwszym przypadku naciąg jest możliwy przy zastosowaniu tzw. śrub rzymskich. Natomiast w drugim naciąg wykonuje się za pomocą pras. Podstawowym problemem w budowie mostów, w tym i lukowych) jest fakt, że praktycznie zawsze schemat statyczny konstrukcji w trakcie budowy i konstrukcji finalnej różni się diametralnie. Dlatego tak ważna, choć często traktowana pobieżnie, jest analiza pracy konstrukcji w stanach montażowych.

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