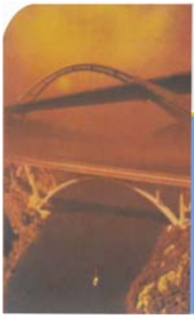

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KRK BRIDGE FROM INCEPTION TO TODAY

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Key words: Concrete arch bridge, cantilever construction, record span, concrete cover, aggressive maritime environment

Abstract: *The Mainland – Krk Island Bridge was constructed in 1980. The bridge comprises two reinforced concrete arches, divided by the St.Marc Island, the Krk I Bridge of 390m span and the Krk II Bridge with the span of 244m. The design and construction of this bridge can still be regarded as an outstanding engineering achievement, even nowadays after almost thirty years of its completion. The bridge design was performed by the engineering office of the Mostogradnja Engineering Company, entrusted with its construction and took into account all the basic principles of bridge design, aesthetics, economy, the available construction equipment and speed of construction. Both arches were constructed using precast elements by cantilevering, temporarily stayed from the shores across a system of steel stays. In order to reduce forces in auxiliary stays, utilized to provide cantilevered support to the arches during construction, the arches were constructed in two or more stages, the central cell of box girder being constructed first, followed by side cells, subsequently concreted in-situ following completion of arch crown. It was thus accomplished that the quantity of auxiliary steel stays remained the same as for the construction of the Šibenik Bridge of 251m span, making the construction very economical. Unfortunately, due to the extremely thin concrete elements employed for arches, spandrel columns and the superstructure and consequently very small concrete cover in an aggressive maritime environment, very soon chlorides from the salty sea began to penetrate into the structural elements and the maintenance of this bridge became a big problem.*

1. INTRODUCTION

The idea of building a bridge which would link the Mainland with the biggest Croatian island Krk has been pursued for a very long time, though many years have passed from idea to realization. Finally in 1975, construction funds were raised and it was to be decided about the future bridge structure. In a very tough competition with different domestic and foreign proposals (suspended bridges, continuous beam structures, beam structures with inclined cables, steel arches), the solution with reinforced concrete arches was chosen as the best one in technical, economical and aesthetical respects [1],[2],[3].

It was necessary to develop technically reliable and economically acceptable solution across 465 m wide water table, but the one which could be executed in circumstances of that time. It has to be mentioned that designer of the bridge, Ilija Stojadinović was working for Mostogradnja Engineering Company, the main contractor of the Krk Bridge. The company also constructed the Šibenik and Pag arch bridges. Therefore, design solutions were in many aspects determined by the available construction equipment and acquired experience and knowledge of the contractor. The construction procedure of the Krk Bridge was in a way an improvement of methods utilized to build previous arch bridges, so their construction will be briefly described.

The reinforced concrete arch of the Šibenik Bridge, completed in 1966, was constructed by free cantilevering method (Figure 1). The arch span is 246 m with a rise of 31 m (Table 1). Segments of the arch were concreted on a scaffolding platform, 27 m long. The arch cantilevers were supported by stays anchored into the strong abutments, using 30 m tall auxiliary pylon positioned on the bridge superstructure above abutment. Auxiliary supporting stays were made of steel profiles and prestressing tendons, which considerably increased their load carrying capacity. After completion of one segment, the scaffolding was moved forward by a floating crane. The box type arch cross section was not concreted as a whole, as voids were left in the top and bottom flanges, thus reducing the dead load and consequently, decreasing forces in stays. These voids were concreted after the arch was closed at the crown.

The arch construction cantilevering method was further developed in the construction of the Pag Bridge, completed in 1968 (Figure 1). The arch span is 193 m with a rise of 28 m (Table 1). An auxiliary bent at the end of a cantilever was used instead of the pylon. Backstays of the Pag Bridge were anchored directly into the ground. Diagonal ties holding the next arch segment were placed over the bent, so that the whole construction procedure was simplified. Another useful innovation was partial casting of the arch cross section, which was utilized for the crown segment.

location	construction period	arch span l (m)	arch rise f (m)	f/l	l^2/f	arch depth d (m)	d/l (average)	concrete of arch (m^3)
Šibenik	1964-1966	246.4	30.8	1:8.0	1971	2.9-3.7	1/75	2001
Pag	1967-1968	193.2	27.6	1:7.0	1352	2.3-3.0	1/73	1006
Krk I	1976-1980	390	60	1:6.5	2536	6.5	1/60	5500
Krk II	1976-1980	244	47	1:5.2	1264	4.0	1/60	1500

Table 1: Basic data of Šibenik, Pag and Krk Bridges, Croatia

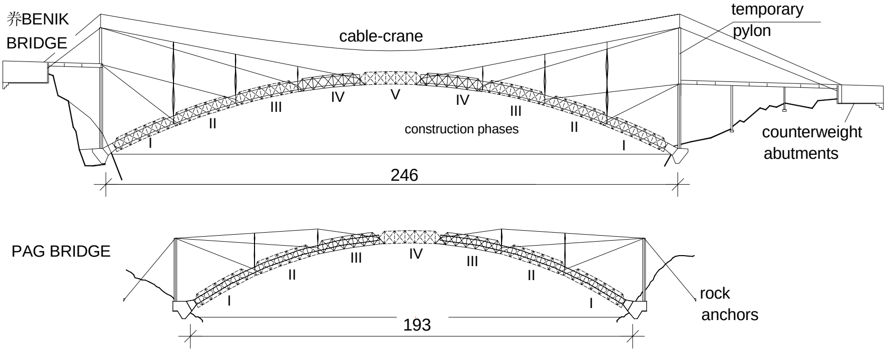


Figure 1: Construction procedure of Šibenik and Pag Bridges

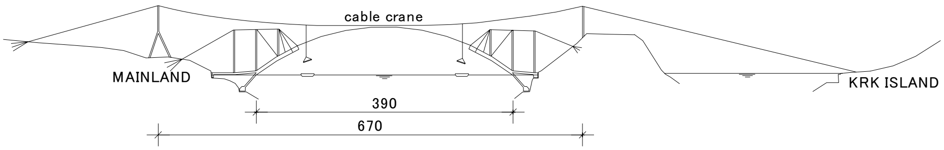


Figure 2: Construction procedure of Krk I Bridge

This idea of partial casting of the arch cross section was again applied on the Krk Bridge arch [4]. The technique of the free cantilevering procedure had to be essentially adjusted because only two cable-cranes of 10 tons capacity each were available for local transport on site. Arch segments of Krk I (390 m) and Krk II (244 m) bridges were prefabricated on a barge, placed in position by cable-cranes and then assembled in situ by concreting “wet” joints (Figure 2). The central arch part was erected first, after which it served as scaffolding for subsequently built lateral arch parts. The procedure resulted in more than 10 000 m’ of longitudinal and transverse joints on the larger Krk I arch.

The very daring construction method without classic scaffolding and applying original and bold design and construction ideas, adjusted to specific location conditions and building equipment, available to the contractor, undoubtedly played the decisive role in the realization of such a span, but unfortunately also resulted in many weak spots in the structure, the issue to be addressed to in the section on the Krk Bridge maintenance.

Despite some, from today’s point of view, incorrect design decisions, this bridge still is an outstanding accomplishment in many respects. The Krk I bridge arch between the Mainland and St. Marc Island with its 390 m span is still the world record holder for classically built concrete arches. The bridge aesthetical appeal is exceptional, fitting perfectly into its surroundings and giving the impression of almost flying above the sea straits, constructed from so very slender structural elements. With considerable reduction of construction costs and also of duration of works, the building procedure of the Krk Bridge significantly contributed to the improvement of construction methods for concrete arches, thus making concrete arches competitive again for large spans, after many years of rejection [2].

2. BRIDGE LAYOUT

The design of the Krk I Bridge was a very demanding task, because an arch bridge of such a large span has never been built before [1].

A study on arches revealed that in spans exceeding 300 metres, quantities of concrete used for the arch, despite favourable rise to span ratios, increased rapidly, while in spans longer than 400 metres the increase was disproportionally large. Many alternatives with different concrete grades and rise to span ratios were considered and finally, it was concluded that the construction of a concrete arch of 400 m span was possible. On the basis of conducted analysis it was not possible to determine the most appropriate span of the bridge, though and therefore a different approach had to be taken. The deepest executable foundation was to be found in order to achieve as small a span of the arch as possible. Quite a few various alternatives were considered, but finally the solution with foundation blocks laid 19 metres below sea level and with a triangular structure to support arch abutments was found, which made possible the construction of a 390 m span arch across 465 m wide water table.

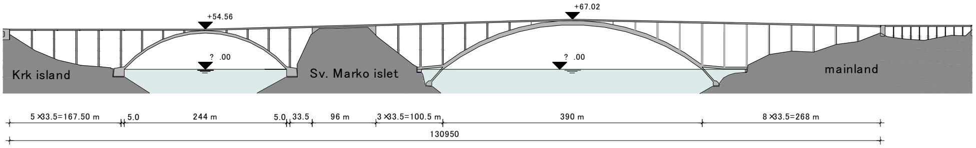


Figure 3: Bridge layout

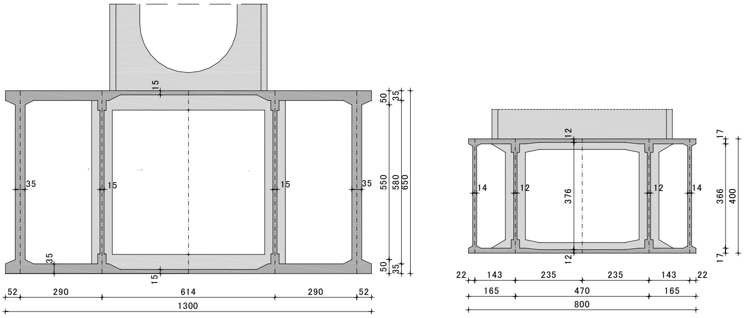


Figure 4: Arch cross section: a) Krk I b) Krk II

As already mentioned, the Krk Bridge (Figure 3) actually comprises two reinforced concrete arches, the Krk I (390 m) and Krk II (244 m). The smaller arch is located between two islands – the Krk and the St. Marc Island across the Windy Channel, while the longer one connects the Mainland to the St. Marc Island crossing the Quiet Channel. The rise of Krk II arch is 47.5 m, resulting in the rise to span ratio of $f/L=1/5.14$ and the rise of the Krk I arch is 60 m, with the rise to span ratio of $f/L=1/6.5$. The Krk II arch is fixed to arch abutments on sound rock, while the Krk I arch is elastically fixed, with both its abutments fixed to the horizontal beams of triangular concrete structures under the sea level. Both arches are of three cell box type cross section with constant outer dimensions along the entire length of the bridge (Figure 4). The arch width was defined as 1/30 of the arch span and the depth as approximately 1/60 of the arch span. Consequently, outer dimensions of the smaller arch were chosen as *b/h*=8.00/4.00 m and of the larger one as *b/h*=13.00/6.5 m. The shape and size of the arches were determined not only according to structural demands, but also to construction procedure, economical issues and aesthetics. Building the arches of constant outer dimensions had great advantages regarding prefabrication and assembly of arch elements. More than 60% of the larger arch and 86% of the smaller arch was constructed using precast elements. External webs of the box type cross section were designed as double T-section in order to achieve visual reduction of the arch depth along the whole length from abutments to the crown.

The Krk I arch abutments are supported by triangular structures, comprising nearly horizontal beams and struts, inclined at an angle of 50° to the horizontal (Figure 6). The horizontal beams of 33.5 m span, extending to the shores, are of box type cross section of varying dimensions from 4.82×13.0 m at the arch connection to 3.0×20.0 m at the other hinged end of the beam. Inclined struts are approximately 21 m long, with constant depth of 2.2 m and width varying from 13 m on the top to 17 m at base. Reinforced concrete foundation blocks of average dimensions 6.0×20.0 m, embedded in the sea bottom, support the struts, built at almost equal sea depth on both sides.

Arch abutments are connected to the inclined struts by concrete Freysinnet type hinges, constructed by reducing the contact area to 1/3 of the strut width and fixed to the horizontal beams. Layouts of the arch supports are not the same on both banks, due to different terrain and geotechnical conditions. On the Mainland side, an additional supporting structure, comprising a horizontal 33.5 m long slab and a vertical side wall of 2.5×20.0 m dimensions, had to be added behind the horizontal beam of the arch abutment, to increase the stability of the sound rock in taking up the large arch thrust.

Abutments of the smaller arch are of standard shallow type, embedded 4.0 m deep into the sound rock, with dimensions 9.0×12.0 m at the base.

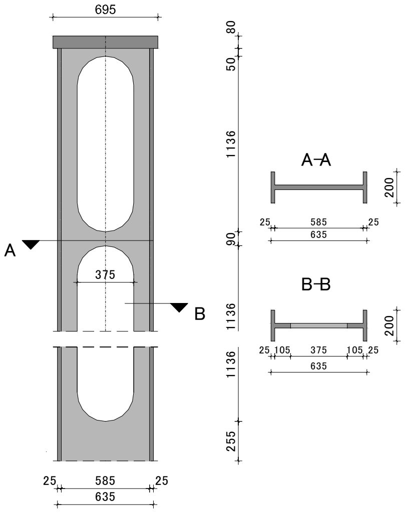


Figure 5: Column cross sections

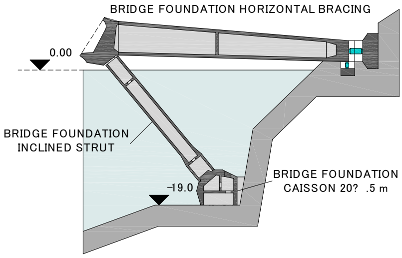
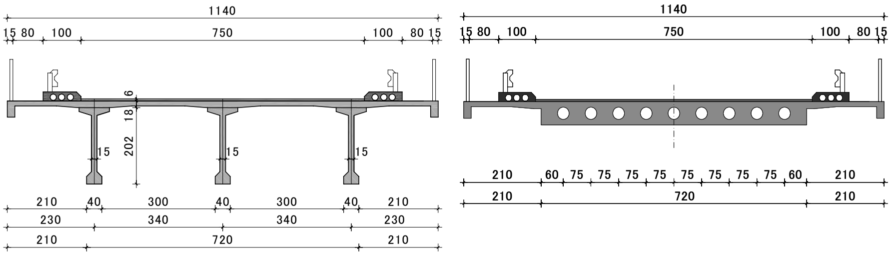


Figure 6: Foundation of Krk I arch at St. Marc Island shore

Columns consist of two extremely slender T-shaped cross sections interconnected by precast cross girders at a 12 m distance (Figure 5). Large voids were designed in order to reduce dead load on the arch. The shape of the columns was adjusted for application of the slip forming method for their construction. Spandrel columns are elastically fixed to the arch and columns on shores are founded on shallow slab foundations in the limestone rock. The 11.4 m wide bridge deck is almost entirely made of precast elements. It comprises a grillage system of precast prestressed concrete longitudinal girders and cast *in situ* cross girders, placed at the thirds of the span to enhance the grillage behaviour and above supports, connected by a precast concrete deck plate with elements 11.0 m long and 5.5 m wide (Figure 7a). Longitudinal joints of the deck plate were executed on the top of the central girder upper flange and transversal joints on tops of cross girders. The deck plate is connected to longitudinal girders by shear connectors. The static system of the deck is a series of simply supported spans, not affected by uneven vertical displacement of supports unlike the continuous structures. Strong head beams in entire superstructure width were constructed on tops of all the columns. The bottom of these cross beams was aligned with the bottom of the deck structure and thus concealed, which resulted in a nice appearance, but it also meant that the depth of the longitudinal deck girders had to be adequately reduced at supports, what is structurally not the best solution. Besides, the longitudinal deck girders were placed on hammerheads concrete on concrete, without utilizing structural bearings. This enhanced the stability of the slender columns, as they were longitudinally and transversely constrained by the deck through friction, but again this is not a solution, that can be recommended for the nowadays practice. Only the part of the deck above the arch crown segment was cast *in situ*.



a) above arches

b) access bridge

Figure 7: Superstructure cross section

The access bridge is approximately 130 m long to avoid very tall approach embankments. The deck of the access bridge is a cast *in situ* voided reinforced concrete slab (Figure 7b). The voids were constructed, utilizing cardboard made pipes. The access bridge and the main bridge are separated by a wide pier [1].

3. BRIDGE CONSTRUCTION

Arches of bridges Krk I and Krk II were constructed by cantilevering truss method, the construction procedure where the arch and spandrel columns above the arch are constructed simultaneously. As mentioned earlier in the text, this construction procedure was developed from the experience gained in construction of previously built Pag and Šibenik bridges. Numerous modifications were used not only to improve the procedure, but also to speed up and facilitate construction of arch structure [1],[5]. The most important changes in the procedure are as follows:

- use of spandrel columns in the cantilever procedure thus forming a Pratt type truss during all construction stages,
- arrangement of stays with multiple centres of support,
- method of anchoring stays to the ground through relatively small concrete block fixed to the sound rock by prestressing cables,
- partial casting of the arch cross section and use of precast elements, and
- assembly of steel trusses at the arch crown in order to speed up the arch closure.

The most critical and demanding part of construction process was the execution of arches, so that the entire site was organized to facilitate this task (Figure 8), including concrete production and its transport, prefabrication, transportation and assembly of concrete elements and finally concreting of joints between precast elements. An effort was made to use specialized equipment , such as cable cranes, barges and tower cranes, simultaneously for all construction works, not only for arches [2].

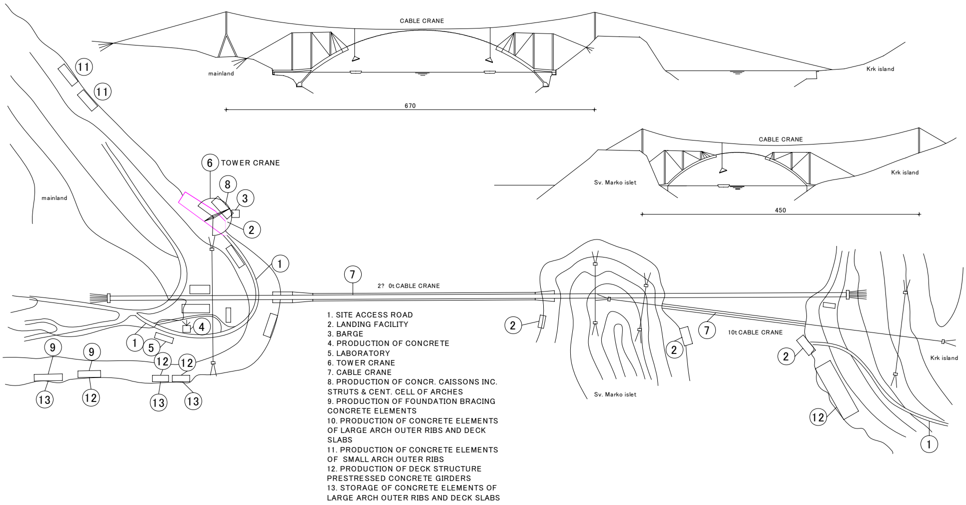


Figure 8: Construction site organization

The arch cross section construction was divided in a few stages to reduce forces in stays, which would otherwise have to support 5500 m^3 of concrete in the longer arch [1].

The central arch cell of the arch was assembled first by cantilevering and when completed, served as load carrying element for suspended scaffolding and formwork for concreting side cells. Side cells were concreted after installation of hydraulic jacks in the crown. The central section of the arch was subjected to large vertical and horizontal actions during construction and it was therefore necessary to adjust its shape and size. It was shaped as a very large box in order to achieve big inertial stiffness, but with minimum wall thickness to reduce the self weight [2].

Stays supporting the cantilevered arch were attached to multiple centres of support, which was made possible by using spandrel columns executed simultaneously with arch elements, as auxiliary elements during the assembly of stays. In addition, an extended horizontal anchored stay was installed and thus it was accomplished that stays, spandrel columns and previously built sections of the arch formed a Pratt type truss during all construction stages. The originally planned construction technology was changed several times during bridge execution, when new circumstances provided an opportunity to carry out operations in a more economic way. These modifications in execution procedure could be accomplished only in a very tolerant cooperation of all parties involved in the construction process. The bridge designer was present at the site throughout the construction, monitoring every phase of building process and participating in solving all problems [2].

3.1 Foundations construction

Rock excavation to level the sea bed for the placing of foundations of the inclined struts was executed with horizontal and vertical cuts, made by underwater blasting, subsequently to borings done with the help of drilling equipment, installed on a barge (Figure 10). Loosened material was excavated by dredgers. Thus, a horizontal sea bed surface was formed to allow lowering of the Krk I bridge caissons onto it (Figure 9).

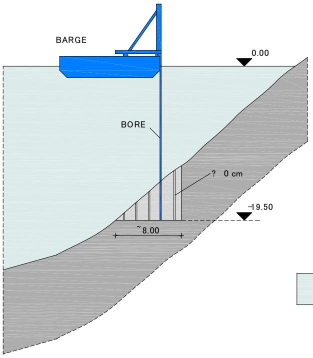


Figure 10: Execution of underwater boreholes

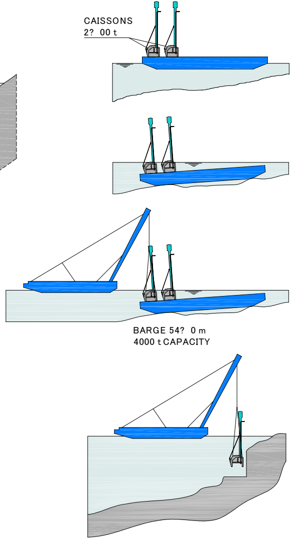


Figure 11: Submerging of caissons

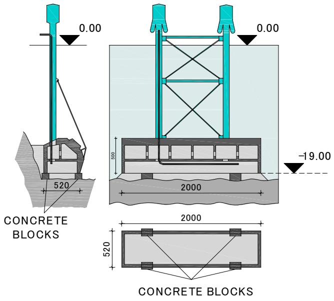


Figure 9: Placing of caisson

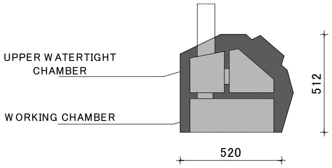


Figure 12: Caisson cross section

Caissons for the inclined struts foundations, comprising box type elements of 35 MPa grade concrete, were precast on a barge and filled with concrete after its submerging (Figure 11, Figure 15). The cross section of the caisson (Figure 12) consisted of a watertight chamber above the working chamber, designed to reduce the caisson weight of 500 tonnes, as a result of buoyancy. Hence, the weight of submerged caisson was only 140 tonnes. Caissons were submerged together with a barge, then transferred by floating crane to position and finally lowered 19 m below sea level to previously formed horizontal surface, levelled with 4 blocks concreted under water. The working chamber was filled with pumped concrete, after removing water from it using compressed air. The upper chamber was filled with concrete at atmospheric pressure few days later. Finally, the space between the caisson and rock ground was filled with concrete.

Inclined struts of 600 tonnes weight were constructed in a very similar way. They were concreted on a same barge as caissons, submerged together with it, transferred as 80 tonnes load due to buoyancy by floating crane to the final position, lowered to the caisson and then the upper part was supported by a horizontal stay anchored to the rock (Figure 13). Struts were filled with concrete after pumping out of water. The ingress of water to the struts interior was prevented by transverse diaphragms with closed lids at both ends of the struts.

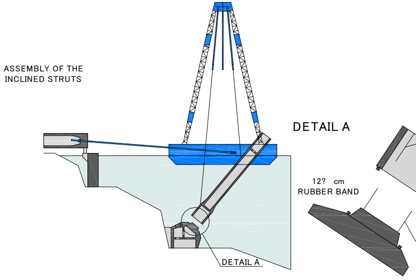


Figure 13: Caisson and strut connection

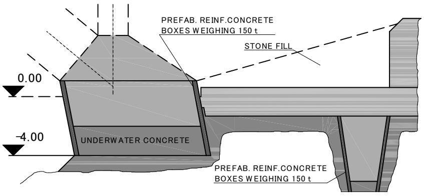


Figure 14: Foundation of Krk II Bridge arch on Krk Island

Horizontal beams of arch abutments comprise three prestressed concrete precast elements 33 m long, weighing 320 tonnes, each. After execution, precast elements were transferred to the arch foundations by a floating crane. One end of the beam was placed onto the inclined strut and the other to foundation of adjacent pier.

The 180 tonnes heavy reinforced concrete support blocks at arch abutments, utilized for load transfer from the arch to support elements, were installed by a floating crane.

Reinforced concrete foundations of the Krk II Bridge arch (Figure 14) were constructed in a construction pit. The hollow concrete box weighing 150 tonnes was lowered into the construction pit by a floating crane. The lower part was concreted with underwater concrete. After reaching the required concrete strength and pumping out of water, the remaining part of the foundation was filled with concrete. The foundation at the Krk Island shore had to be widened because of deteriorated rock [2].

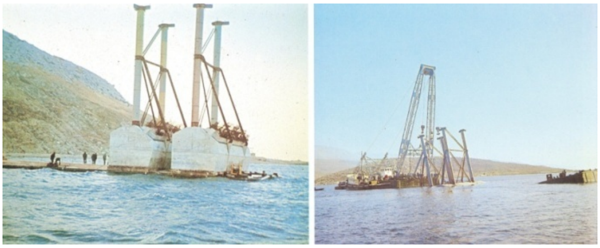


Figure 15: Photos of submerging of a barge with caissons

3.2 Construction of the arches and columns

The assembly of the central section of the Krk I Bridge arch was divided in two stages. The central box when completed was not sufficient to provide stability of the arch during construction and therefore a 1.5 m lateral widening of the upper and lower flange had to be executed [1]. Even this widened cross section (Figure 17) could not transfer all loads of side sections, so that the lower flange of side cells had to be executed first and subsequently the upper flange, following the installation of hydraulic jacks at the crown, utilized to transfer loads from only the central cell to the complete until then constructed arch cross section. The last stage of arch construction consisted of concreting joints between flanges. It should be noted that by applying the partial casting of the arch cross section, the values of stay forces during cantilevering were roughly the same as in previously built bridges of considerably smaller spans. The utilization of precast elements significantly reduced construction time, which otherwise would have taken considerably longer, because of the staged construction of the arch.

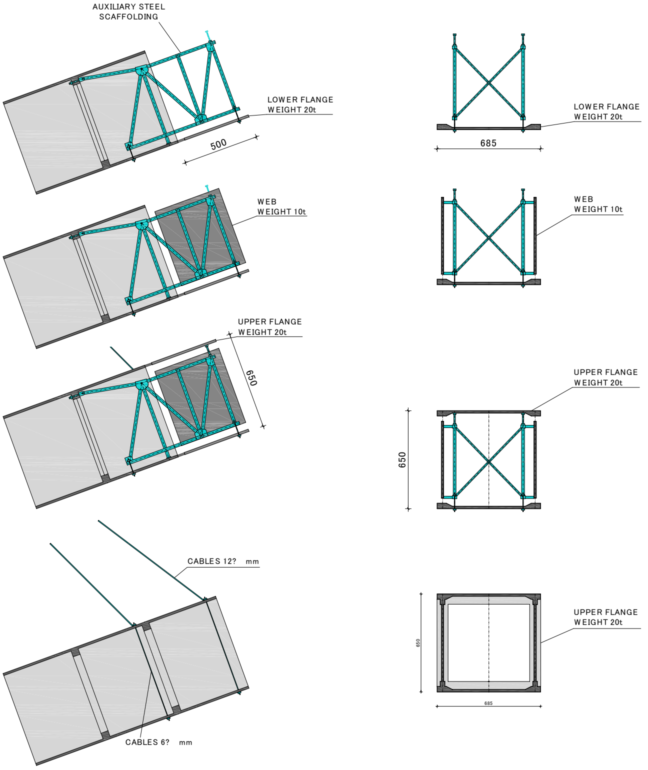


Figure 16: Assembly of central arch cell

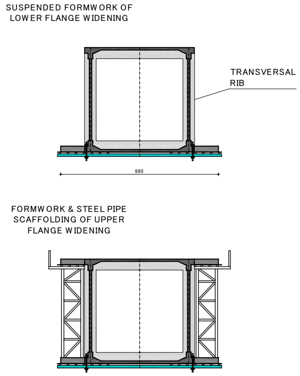


Figure 17: Concreting of arch upper and lower flange widening

The central arch cell was constructed in approximately 5 m long precast elements of 50 MPa concrete grade, consisting of 20 t upper and lower flanges, and 10 t webs. Elements were concreted on the shore or on large barges in horizontal position, therefore providing good concrete quality and execution precision. Precast elements were transported by a barge to a place reachable by cable cranes, which were then used for erection and assembly of elements on cantilevered truss scaffolding (Figure 16). After positioning, they were fixed to the previous segment. When the grade in concreted joints reached a value of 30 MPa, the central cell was prestressed by two vertical cables at its front end and then supported by diagonal temporary cables onto the top of the preceding column.

A delay of only one day in reaching the required 30 MPa concrete grade would elongate central cell completion for almost 3 months and therefore the concrete mixture was designed to attain this value in as short a time as possible [2].

The assembly of one segment and the relocation of movable truss scaffolding were usually completed in one day. One arch segment with all stages (formwork, reinforcement, concreting of connections of precast elements and transverse stiffeners as joints to the preceding segment) was finished in a few days, depending on the weather. It was necessary to wait approximately a week between the release of steel truss scaffolding and prestressing of cables, to allow for the hardening of the concrete of joints, so that one segment was usually completed in 6 days [2].

After completion of the first few arch segments, the arch was tied by a diagonal stay to the top of the previous column and the temporary diagonal cables were then dismantled (Figure 18).

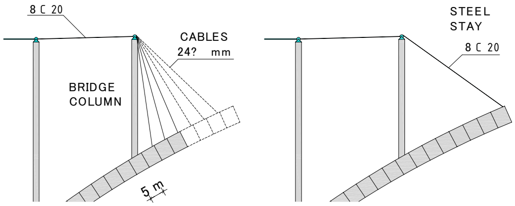


Figure 18: Prestressing cables supporting segments of arch central cell

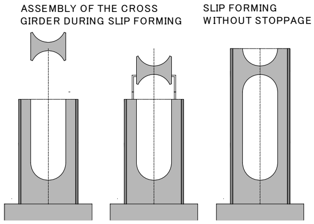


Figure 19: Slip forming of columns

Stays comprised rigid steel sections and prestressing cables. Prestressing cables were used to strengthen steel sections, depending on the required force. When steel cross sections load capacity was reached, cables were prestressed, thus unloading the steel sections. Rigid stay steel sections were loaded and unloaded repeatedly, as the construction went forward.

Anchor stays were attached to relatively small concrete block, which was fixed to the ground by prestressing anchor cables to transfer very large ensuing forces safely into the rock.

Spandrel columns as load bearing members during construction had to transfer fairly substantial loads to the arch, so they were constructed of larger size than auxiliary columns used in construction of previously built arches. It was determined by static and cost analyses, that permanent spandrel columns might be used as load carrying elements of the scaffolding without additional strengthening, while auxiliary columns would have to be removed once the arch has been completed, so that the difference in costs of using permanent spandrel columns instead of auxiliary ones was not significant [1].

The construction of spandrel columns, utilized during the construction as vertical members of the Pratt type truss system, proceeded simultaneously with the arch construction. The shape of the columns was adjusted for slip forming procedure and prefabricated cross girders were used to speed up the construction process (Figure 19). Two T-shaped sections of constant dimensions were concreted by slip forming along the entire height, usually in lengths of 10 metres in 24 hours. Even the highest columns could be completed in several days by applying this construction method. The originally planned procedure was changed during construction, because of the problems caused by sticking of concrete to the formwork during work stoppages. The solution comprising steel pipes with shoes, constructed in the upper column parts to provide support for cross girders, enabled continuous slip forming without work breaks. The construction of a single column, including concreting the base, concreting the cap beam and assembling auxiliary concrete columns on top to provide the connection with the preceding column by a horizontal steel stay, was completed in 15 days [2].

The Krk I arch comprises 40 symmetrically built segments, while the Krk II arch consists of 26 symmetrically built segments. Despite frequent delays and suspensions of works because of rain and strong winds (for example in May 1978 construction site recorded 21 day without works due to poor weather conditions), the central cell of Krk I arch was assembled in only 13 months, while Krk II arch was completed in only 5 months [2].

Figure 20: Photos of arch construction

Few improvements of the construction procedure were very important for the reduction of construction times, such as the erection of the arch base (initial) segments by floating cranes and the placing of temporary steel trusses at the crown to facilitate the activation of hydraulic jacks there, before the arch closure [2],[3].

When the first segment of the Krk I Bridge arch was to be assembled, another floating crane was operating at a pipeline terminal near the bridge, so it could be used to work together with the contractor floating crane (Figure 21a). Their combined capacity amounted to 500 tonnes, which was enough to erect the arch base segments. First two segments, each 38 m long, were concreted on a barge and then erected with cranes in only 3 days, thus shortening the arch construction for at least 45 days. Voids were left in upper and lower flanges of the segment to reduce its weight.


a) Krk I Bridge b) Krk II Bridge

Figure 21: Photos of lifting base segment

Several sections before the arch closure, two steel trusses were assembled by cable cranes to provide support for the installation of hydraulic jacks at the crown. Thus, the completion of the arch was speeded up, the mismatch between the two cantilevered ends could be corrected on time and stresses in all elements of the scaffolding, stays and spandrel columns decreased and vertical deflections of cantilevers were significantly reduced. Hence, the utilization of steel trusses significantly lowered construction costs [2].

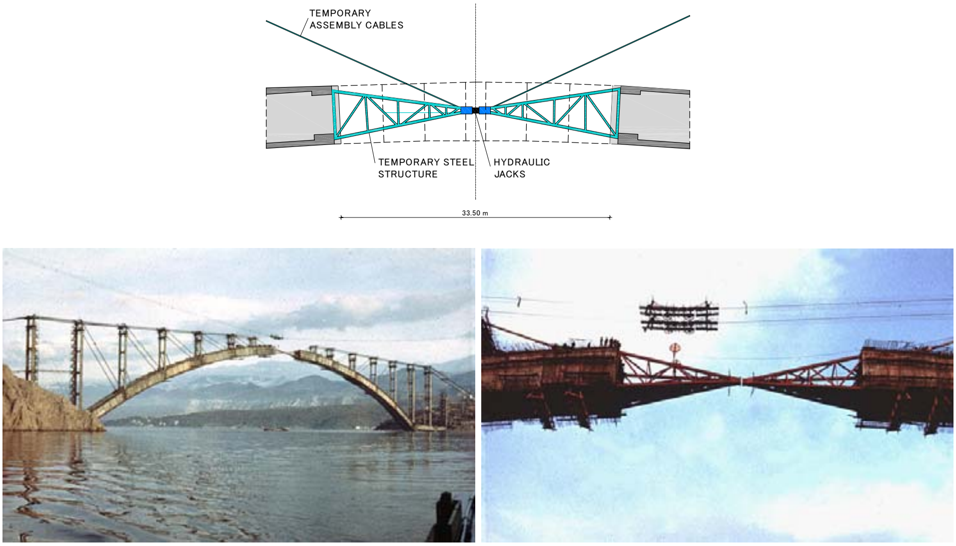


Figure 22: Steel trusses at Krk I arch crown

Steel trusses on the Krk I arch (Figure 22) were approximately 18 m long and they supported construction of 6 arch sections, of approximately 35 m overall length. Four hydraulic jacks were installed, providing a force of 1000 tonnes.

Trusses on the smaller arch were shorter, because only one cable crane was available, so that they could support the construction of 4 arch segments, 25 m long.

One rather unpleasant event happened in winter 1979 after activating hydraulic jacks at the crown of the Krk I bridge. The temperature dropped for 20 degrees causing icing on the arch and shortening of the cantilevers, which resulted in significant reduction of the jack forces. Cantilevers started to move horizontally due to the strong wind reaching speeds of 140 km/h, causing the girders together with hydraulic jacks to fall into the sea. Soon after the event, another set of hydraulic jacks was placed at the crown [2].

Connections of precast elements (Figure 23) were executed by overlapping U shaped reinforcement in addition with longitudinal reinforcement (Figure 24). The 1.5 m widening of flanges was concreted in the segment of the arch between two previously built columns, simultaneously with the execution of the central arch cell. The widening of lower flange was executed using scaffolding suspended from the central cell bottom flange, while the upper flange was concreted on steel pipe scaffolding laid on the lower flange (Figure 17).

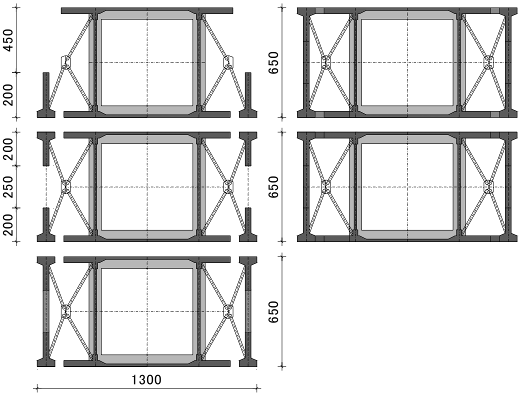


Figure 23: Construction of Krk I arch side cells

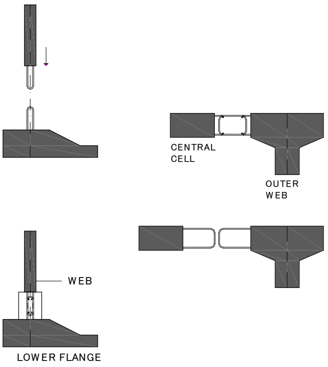


Figure 24: Connecting reinforcement of precast elements

The construction of the Krk II arch started 6 months after the beginning of works on the Krk I bridge construction. The first segment was concreted in one 32 m long piece weighing 360 tonnes (Figure 21b). Segment sections, concreted on the shore, were moved by floating cranes to a barge. The barge was then positioned so that the segment could be attached to the arch abutment by a temporary steel hinge, which was then used as a pivot for lifting the segment into position by a floating crane. Finally, the segment was tied to a diagonal stay. The construction method of the arch cell (Figure 25) was similar to the one used for large arch, except that the elements were considerably lighter. The smaller arch of 244 m has a very favourable high rise and because of that the arch construction proceeded straightforwardly. The central arch section was cantilevered in its entire length and after completion it could carry the weight of both side cells. Webs of the arch side cells weighing

60-90 tonnes were prefabricated in their entire height as I-shaped sections. The length of precast elements was determined by the assembly capacity of available equipment, floating cranes for arch segments at smaller heights and cable cranes for higher segments. Hydraulic jacks at the crown were activated after the construction of side cells was completed [2].

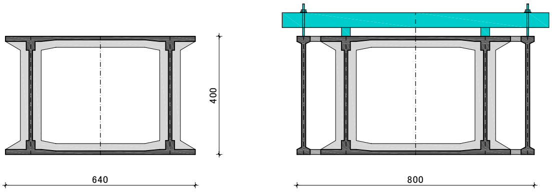


Figure 25: Krk II arch central cell

3.3 Superstructure construction

Precast prestressed longitudinal deck girders were erected by a movable steel launching truss. This standard construction procedure lasted 2 months.
Precast deck slabs weighing 24 tonnes were erected using a floating crane and steel portal cranes with winches. A 300 tonnes capacity truck crane placed on top of a barge was utilized for the erection of precast deck slabs above both arches [2].

The construction of the bridge commenced in August 1976, and it was opened for traffic in June 1980 [1].

Figure 26: View of Krk Bridge

4. BRIDGE MAINTENANCE

The Krk Bridge was built in an aggressive maritime environment. Environmental influences are the following [6]:

- ingress of chlorides from the sea with salinity between 3.5% and 3.8% of water mass, while in the Baltic sea for example it is only about 0.4%,
- strong winds during winter causing salt spray, depositing chlorides on all structural elements,
- high summer temperature facilitating the chloride penetration and thus causing reinforcement corrosion, and
- frosts happening from 10 to 15 times every winter.

The Krk II structure across the Windy Channel between the Krk and St. Marc Islands is particularly affected, because the strong *bora* winds are blowing directly on it. The Krk I arch is less influenced by strong winds, as it crosses the Quiet Channel between the Mainland and St. Marc Island.

Results of inspections and testing revealed degradation of structural parts, as shown in Table 2.

PROBLEM	CAUSE
Superstructure	
• cracking of the anchor zones (girder ends and pier tops)	• no bearings installed
• local corrosion	• poor solutions of roadway drainage
Piers	
• cracks, delaminations, reinforcement corrosion	• problems with slipforming – poor workmanship • concrete cover smaller than designed
Arch	
• underwater elements attacked by sea fauna (shells) • ingress of chlorides into concrete	• designed coating of exposed surfaces has never been performed

Table 2: Detected problems

Structural defects were found at an early age and hence cannot be blamed only on the aggressive environment, but may also be attributed to conceptual design and errors and negligence on site. Design errors can be summarised, as follows [7]:

- misinterpretation of the codes in designing very small concrete cover,
- extensive usage of precasting not supported by satisfactory constructional detailing,
- underestimated effect of creep and shrinkage,
- placing the precast prestressed girders of the superstructure directly on tops of piers with no fixed connection and no bearings (Figure 27), and
- inadequate drainage systems.

The worst deterioration is the reinforcement corrosion caused by high chloride content, which penetrated into concrete. According to conducted investigations, in the more exposed

Krk II Bridge arch (244 m) chloride content in reinforcement region exceeded the critical value of 0.1% of the concrete (0.4% of the cement mass). Relatively good condition of the concrete cover is probably due to high concrete grade, more than 80 MPa, made from a mixture with added blast-furnace slag.

Effects of creep and shrinkage were underestimated. For the Krk I bridge (390 m span) jacks were used to raise the arch for 63 mm after two years of service and for additional 93 mm after another year, and then they were encased in concrete.

Poor detailing of the superstructure supports on the Krk bridge, with main longitudinal prestressed girders resting directly on the piers (no bearings) caused heavy cracking both in the anchor zones of the girders and in the pier cross-beams supporting them.

All bridge piers for both the Krk bridges have deteriorated considerably. The execution by slip forming was poor, with concrete cover at some places only 1 cm, even smaller than the designed concrete cover of 2.5 cm and with dubious variable concrete quality.

The underwater examination of inclined struts in the sea, utilized for the foundation of Krk I arch revealed that concrete has been attacked by sea flora and fauna. The most destructive is the shell Rocellaria Dubia, which drills the holes 5 to 10 mm in diameter and 10 to 30 mm deep in concrete. Ten years ago maximum density of holes 4 to 6 m below the sea level was more than 4000 units per m^2 of surface and now it is more than 8000 units.

The protection of all exposed arch surfaces by coating, as specified in the design specifications to be carried out immediately after the end of construction, was not done due to the lack of funds.

The application of concrete protection measures started immediately after the bridge was opened to traffic. Almost all known methods of repair and protection of reinforced concrete structures in marine environment were tried, but most of them failed and even accelerated the reinforcement corrosion, because 1-2 cm of very good concrete was replaced with very permeable mortar. Even the best protection systems applied in 1990 helped only by absorption of chlorides in the added mortar and prolongation of their penetration in the structural concrete. By the end of the last century new improved flexible polymer coats for concrete protection from the ingress of chlorides appeared on the market and were applied to the exposed surfaces of the Krk I. The chosen protection system consists of a high quality polymer-cement mortar with compressive strength of over 50 MPa, adhesion strength to concrete of at least 2 MPa, with reduced shrinkage and high impermeability and of a chloride impermeable 1.5 mm thick polymer coating [6]. This new system stopped further penetration of chlorides into the structural concrete and is now being applied to all exposed structural surfaces. It is estimated that chloride ions at the reinforcement level shall reach the critical threshold within 20-25 years. So far, the most affected structural elements have been repaired up to the height of 25 m above the sea level. These include the Krk II arch, all spandrel columns of the Krk II bridge and columns on the St. Marc Island, repaired by removing 2-3 cm of outer concrete layer and replacing it with 2 cm of high quality polymer-cement mortar and the protective polymer coating. The same protection system was applied at three other columns and on the inclined strut of the Krk I foundation on the St. Marc Island, but with removal of 1-2 cm of concrete and adding 1 cm of polymer-cement mortar and polymer coating. The works on the inclined strut on the Mainland and the Krk I arch up to the level of 25 m above the sea are in progress. All the remaining outside surfaces over 25 m above the sea level shall be treated with migrating corrosion inhibitors and protective polymer coating.

The repair and protection of high columns on the length of 15 m from the bottom, had to be done by removing 3-4 cm of concrete cover and by replacing it with 10cm of high strength self compacted concrete, micro-reinforced with 50 kg/m^3 of steel fibres.

The most affected high columns on shore, which could have been de-stressed, were strengthened by additional 5 cm of high strength, low shrinkage concrete along the flanges in their entire height, after removal of 2-3 cm of infected concrete cover, up to the transverse reinforcement.

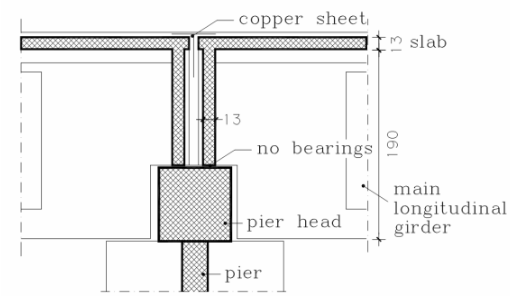


Figure 27: Details of superstructure above the pier (longitudinal section)

Column cross beams on the Krk and St. Marc Island were only patched up, while all the other column cross beams have not been treated so far at all.

As already mentioned before, one of the weakest spots were support details of the deck on columns (Figure 27). Structural elastomeric bearings had to be installed and new prestressed cross beams constructed. This was done on 20 of 31 columns so far.

The repair works on the Krk Bridge are still in progress and will remain so for a long time.

5. CONCLUSION

The Krk Bridge remains an outstanding engineering achievement. All the basic principles of bridge design, aesthetics, economy, the available construction equipment and speed of construction were adhered to. From today's point of view, the efficient construction method, with mostly precast concrete elements, utilized in the Krk Bridge construction cannot be recommended without substantial modifications, since the results of inspections and testing revealed degradation of structural parts, primarily due to inadequate conceptual design, errors on site and exposure to aggressive maritime environment. The economy is lost, because huge resulting maintenance costs were not accounted for.

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