Bridge Erection Techniques and Construction Equipment: Introduction

The technical feasibility and economic viability of building bridges depends heavily on the construction methods available. Over the years, the development of erection techniques and specialised construction equipment has pushed the boundaries of bridge construction ever further. Advanced technologies together with strong competition in the marketplace have led to the development of numerous innovative erection solutions. Bridge construction is also a very visible affair, such that complex construction techniques like heavy lifting and sliding can increase the public awareness on engineering achievements and raise the profile of our profession along the way.

The development of an erection scheme is a challenging optimisation task with many constraints and the target of minimising cost whilst ensuring safety and reliability. Designing the related specialised erection equipment is a multi-disciplinary task at the interface between structural, mechanical and electrical engineering, whereby the equipment has to satisfy numerous requirements and usually be tailor-made or highly adaptable. Safety is paramount and affects design, operation and maintenance. Available design guidance is limited and fragmented, owing to the aforementioned complexities and the pace of development in this area.

The idea for this paper series originated from the work done in IABSE Working Group 6: Bridge Construction Equipment. The aim of this series is to provide an overview of the state-of-the-art in bridge construction and introduce recent advances in this field. It is hoped that it will disseminate knowledge and inspire structural engineers to think outside of standard construction solutions, paving the way to yet more challenging bridge structures and optimising their cost for the public.

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Industrialized Construction of Large-Scale High Speed Railway Projects: The Modena Bridges in Italy

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Abstract

Construction of the 24,8 km Modena Viaducts, which form part of the Milan–Naples High Speed Railway Project in Italy, required full-span precasting of 755 simply supported spans and in-place casting of 9 three-span continuous bridges in only 30 months under global warranty on time, costs, and quality. In this paper, details are given on how such a record-breaking goal has been met.

Custom-designed special construction equipment was used for most of the project. Defining the QA/QC qualifications for design, fabrication, and site operations of equipment took almost 1 year. Analysis of methods, risks, and their mitigations was performed for every major activity. Contingency plans were identified and also prequalified.

Performance requirements, technical specifications, and design criteria were identified for special equipment. Equipment design was subjected to full independent checking. Fabrication of equipment—traceability of materials welding, dimensional control, systems and plants, controls, site assembly, and load testing—and site operations were also ruled by specific QA/QC procedures.

Keywords: full-span precasting; mechanized bridge construction; wheeled span carriers; moveable scaffolding systems.

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Introduction

In the year 1991 the Italian railway authority assigned the design and construction of infrastructures and plants for the Italian High Speed Railway between Milan and Naples to the concessionaire TAV. Within this program, TAV assigned the design and construction of the 182 km section between Milan and Bologna to a consortium.

The 4,89 billion Euro lump-sum contract included global warranty on time, cost, and quality from the consortium.

The work was divided into 19 lots (13 lots of civil works, 3 lots of railway plants, and 3 lots of technological plants). Subconsortium was assigned the 39,5 km civil work lot from 142 + 685 to 182 + 148 km, the 8,0 km duplication of the Modena–Mantova line and the new stations of Modena and Soliera.

This contract included the 24,8 km Modena Viaducts, the 9,2 km bridges of the Modena East and Lavino Interconnections, additional 1,8 km of bridges crossing four rivers and six railroads, 0,4 km of cut-and-cover tunnels and tens of box-culverts. Tasks also included 25,0 km of railway embankment inclusive of base geo-synthetic protection, anticapillarity layer, super-compacted upper layer, and sub-ballast layer in asphalt concrete.

The subconsortium assigned the construction of Modena Viaducts with a contractual deadline of 30 months. The author, as contractor's bridge technology consultant, wrote the QA/QC specs for the entire project (civil works and special equipment) and performed the independent design checking of special equipment.

The railway alignment runs through the suburbs of Modena, hence mitigating the visual and acoustic impact of the new infrastructure was a major concern. The great number of obstructions along the route—highways, railways, local roads, farm roads, rivers, irrigation channels—and the poor mechanical properties of the soil suggested using long viaducts instead of embankments. Bridges would facilitate water flow during floods of the River Po and would avoid hydraulic problems from the shallow water-table in a great number of underpasses.

The Modena Viaducts include five main structures, all twin bridges supporting ballasted single tracks: the 2,1 km Brenner Viaducts over Brenner Highway A22, the 7,1 km Modena Viaducts over the new railway lines of Modena West Interconnection and the River Secchia, the 2,4 km Secchia Viaduct over the River Secchia, the Modena North Industrial Area and the Modena West Interconnection, the 1,5 km Panaro Viaducts over the River Panaro, and the 1,0 km bridges of Modena West Interconnection over rivers and local roads.

High-speed railway viaducts of such length and so near to the ground posed unusual challenges in terms of visual and acoustic impact. The 3,5 m U-section encloses the noisy portion of the train, acts as a sound barrier[1] and confines the train in the improbable event of derailment. Twin single-track bridges provide route redundancy (during maintenance of one track the other track can be in full-speed service) and the spans are lighter, which simplifies construction.

A box girder would have a similar depth to meet the dynamic requirements of high-speed railway bridges, but ballast, track, and sound barriers would add to the total depth. Because of legal noise restrictions, sound barriers may be up to 4 m tall in Italy. They are expensive due to train suction and they are to be maintained. The U-section improves the visual impact of the bridge, avoids the sound barriers, and simplifies inspection and maintenance because most concrete surfaces are directly accessible.

The architecture of the viaducts was enhanced with an elliptical shape for the cross-section's webs, engraved with wide horizontal bands that catch the sunlight at different angles.[1] The rounded shape of protruding bearing plinths was mirrored into pier caps that allow easy inspection of bearings, span retaining systems, antiseismic devices, and the drainage pipes. The columns are simple cylinders devoid of rustication.

In spite of the elegant architecture, the costs of the casting cells for the precast spans were low because of the small area-to-perimeter ratio. The U-section is much easier to cast in one pour than a box girder. Girders with open section also do not require collapsible inner form-trains, which have to be removed through the end support diaphragms. Prefabrication of reinforcement is simpler and the concrete surface to be hand finished is minimized (only the top of webs).

The Modena Viaducts are comprised of 755 simply supported fully precast spans and 9 cast-in-place three-span continuous bridges: 713 precast U-spans are 31,5 m long, 28 units are 29 m long and 14 units are 24 m long. The continuous bridges are 136 m long and the three spans are 40, 56, and 40 m long. For architectural homogeneity all spans have the same U-section.

Span Precasting

The precast spans were delivered along the constructed bridges. So the first task was to identify the most appropriate location for the precasting yard in relation to the construction program. In-place casting of the 9 three-span continuous bridges was a critical task for continuous delivery of the precast spans. A 30 000 m^2 area was identified adjacent to the Modena Viaducts, where a high-tech precasting yard for construction of two U-spans and two prestressed concrete tubs per day was built (*Fig. 1*).

The precasting yard included storage areas for reinforcement and loose materials, an 11 000 m^2 rear shed for prefabrication of reinforcement cages,

Fig. 1: Precasting facility

a 6000 m^2 front shed for the main casting area, a storage area for 16 U-spans for finishing and the predelivery checks, a 2300 m^2 shed for prefabrication of the PC tubs for the remaining bridges of the contract, a three-line batching plant with two-line mixing tower and underground pipeline network to the casting cells, 3500 m^2 storage for six classes of sand and aggregates, and a logistic area.

Prefabrication of the U-spans started with the reinforcement cages in the rear shed. Eight rebar jigs, each as long as an entire span, were serviced by four 12,5 t gantry cranes. The prefabricated cages included bulkheads (skewed according to curvature in plan), anchorages and plastic ducts for 20 longitudinal post-tensioning tendons, reinforcement, earthing network, and all embedded items. No transverse prestressing was necessary in the 0,60 m thick concrete shells to resist lateral derailment loads. After passing the learning curve, prefabrication of the 33 t heavy cage for the standard U-spans took on average 4 days with 11 ironworkers. Two cages were produced per day.

Set-up for partial pretensioning of the precast spans turned out to be too expensive and cumbersome for this application. Pretensioning typically requires longer curing prior to load transfer to minimize the time-dependent deflections, which are critical for high-speed railway (HSR) spans. The costs for additional casting cells would have offset the savings from anchorages and ducts. Post-tensioning was therefore used for the U-spans. Strands were inserted into watertight plastic ducts prior to, during and after pouring of concrete to minimize the weight of the prefabricated cages, extract activities from the critical path, and use the curing time for production.

Initially the span carriers were also used to move the cages from the rebar jigs into the casting cells (*Fig. 2*). Eventually, the increase in delivery time of the U-spans necessitated the use of a specific carrier for handling of the reinforcement cages. A multihook three-dimensional (3D) truss was used to stiffen the cage during delivery.

The front shed had six casting cells for precasting the U-spans. Two parallel casting lines comprised of three fixed outer forms and a rail-mounted inner form were assisted by two dedicated 12,5 t gantry cranes. The outer forms had independent water and compressed-air installations. The inner forms (*Fig. 3*) were equipped with hydraulic distribution arms for placing of concrete. After placing the prefabricated cage into the outer form, the inner form was shifted longitudinally and lowered into the cage to close the casting mould. The only surfaces which had to be hand finished were the top of the webs.

Concrete was pumped from the mixing tower of the batching plant to the two distribution arms of each inner form through two independent wear-resistant pipelines reaching the six casting cells through a network of underground passages. Each feeding line included a 3,2 m^3 horizontal turbo-mixer, a 7,0 m^3 hydraulic agitator, a concrete pump, hydraulic deviators at the nodes of the pipeline network, and the 40 m^3/h tower-mounted distribution arm. Upon completion of span casting, two washing tanks were used to recover the residual concrete and the pipeline washing water. Aggregates and sand were recovered. The washing water fed the washing points of truck mixers or was recycled when batching new concrete.

The batching process was fully automated. The batching rate was controlled by level probes in the agitators and the concrete pumps. The batching plant was also equipped with a truck-mixer feeding point for concreting other structures of the project and as an emergency line in the case of failure of the mixing tower.

Seventy-six wall-mounted electric vibrators with variable frequency on the outer form and 28 vibrators on the inner form vibrated the concrete and removed air bubbles. A standard 31,5 m U-span required 276 m^3 of 45 MPa concrete, which was placed in 4 h.

After 12 to 18 h curing at ambient temperature, the inner form was stripped and moved to the next casting cell, and the end bulkheads were moved back to the rebar jigs. Tensioning all of the prestressing tendons to 38% of the final stress allowed lifting the 700 t heavy U-span and its transfer to the storage area without overstressing the young concrete behind tendon anchorages.

The permanent bearings were aligned onto the support blocks of the storage area before lowering the U-span onto them. Average 5 day storage was necessary to complete post-tensioning, vacuum-grout the tendon ducts, seal tendon anchorages, grout the anchor dowels of bearings, inspect and finish the surfaces, clean and prepare the surfaces of embedded items and perform the predelivery checks in line with the QA/QC procedure.

Span Placement

Two custom-designed wheeled carriers were used to move the U-spans from the casting cells to the storage area and then to final destination. The span carriers, each 10,5 m tall and 57,9 m long, were comprised of two wheeled trolleys connected by a box

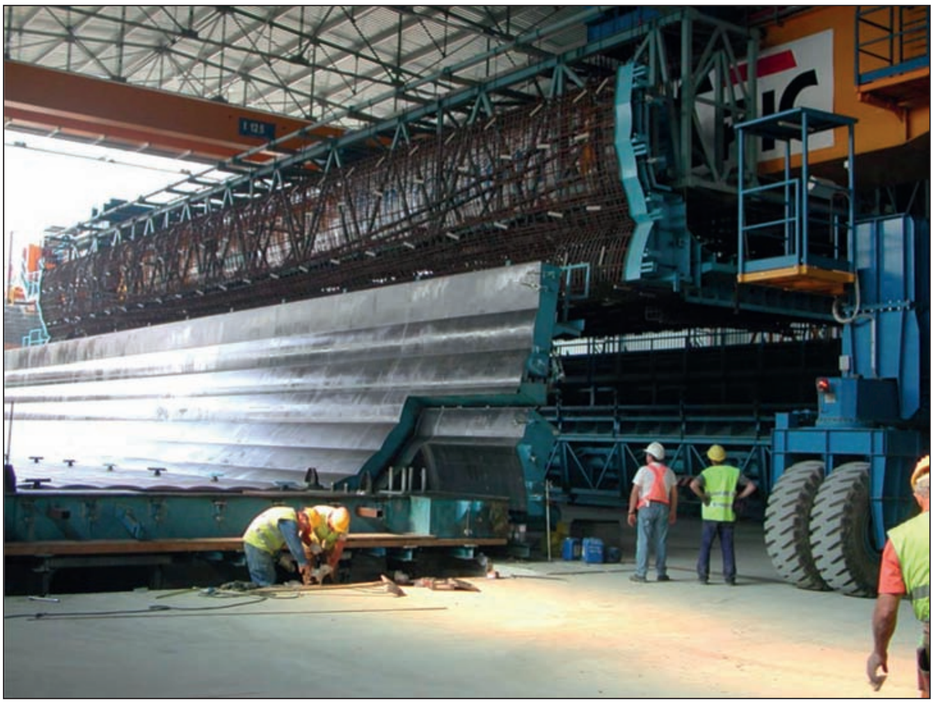

Fig. 2: Placing of the prefabricated cage into the casting cell

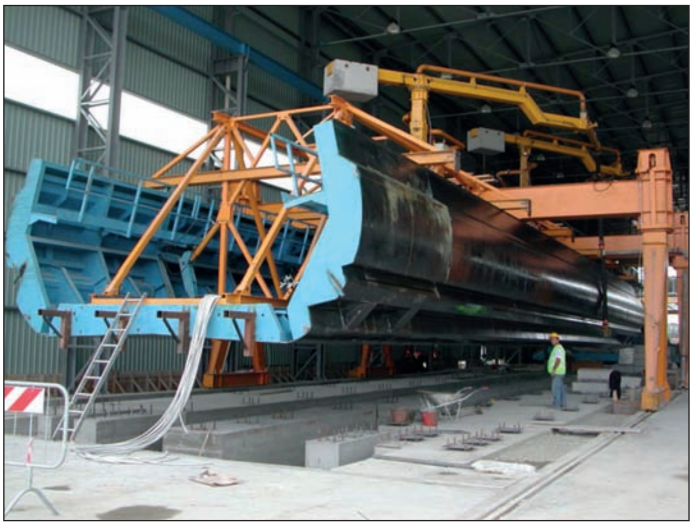

Fig. 3: Rail-mounted inner form

Fig. 4: Span lifting from casting cell

girder supporting two lifting winches. Movement and steering of the trolleys were governed by hydraulic motors and the hydraulic pumps were powered by diesel engines.

The distance between the centerlines of the rear (Master) trolley and the front (Slave) trolley was 45 m. Longitudinal hydraulic cylinders shifted the rear lifting winch to the suspension points of the different types of U-spans while the front winch was fixed.

Picking up the span from the casting cell involved a complex sequence of operations. The carrier was moved alongside the span. For this purpose the 2 three-cell casting lines were separated by a central span transportation route. The trolleys were rotated by 90° by pivoting about support struts. Then the carrier was moved transversely over the span (*Fig. 4*). Each Spreader Beam attached to the span for lifting had two through bolts with distribution plates under the span. After lifting the span the carrier was moved transversely back to the span transportation route and an opposite 90° rotation of the trolleys realigned them to the transportation configuration. The same operations were repeated to release the U-span onto the support blocks of the storage area and to pick it up for final delivery.

After reaching the abutment of the viaducts, an automatic-drive system controlled by ultrasound sensors governed the movement of the carriers within the U-section (*Fig. 5*). The automatic-drive speed was 3,0 km/h at full load (more than 1000 t) and 6,0 km/h unloaded. The wheel distribution was studied so as to avoid excessive stresses in the young spans—the front span of the bridge had only a 6 day curing at delivery of the next span. The carriers were designed for one delivery cycle per day at the maximum distance.

At the front end of the constructed bridge, the front slave trolley of the span carrier reached the rear end of the 78 m underbridge. A self-propelled support saddle running along the underbridge was inserted under the front trolley to lift it until releasing the wheels. Then the translation motors of the front support saddle and the rear master trolley were synchronized to advance the carrier with the front trolley supported onto the underbridge and the rear trolley supported onto the front span (*Fig. 6*). After reaching the span lowering location, the master trolley was locked, the support rollers of the underbridge were released, and the translation motor of the support saddle was inverted to launch the underbridge forward until clearing the lowering area under the span (*Fig. 7*).

The counter-plates of bearings were embedded into the bearing seats during pier construction. The counter-plates of the three directional bearings (fixed, longitudinal, and transverse) were set at the design elevation and the counter-plate of the multi-direc-

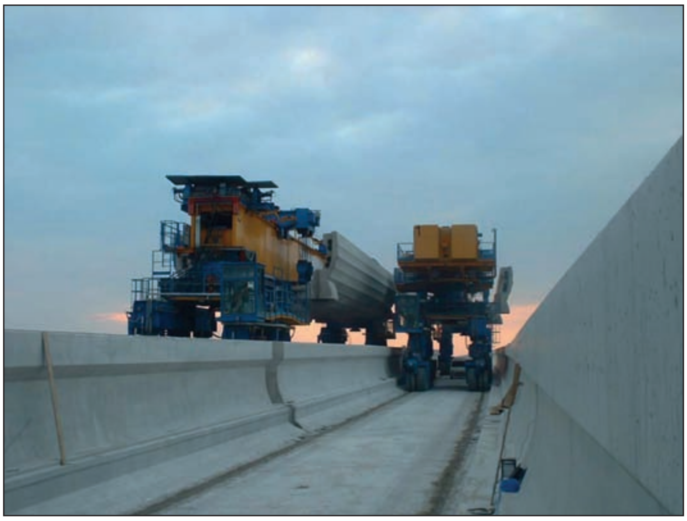

Fig. 5: "Span racing"—delivery along complete bridge

Fig. 6: Wheeled carrier advancing along the underbridge

tional bearing (without dowels) was set 5 mm below the design elevation. The U-span was lowered onto four electronic load cells placed onto the counter-plates of bearings. After adjusting the support reactions to the design tolerance with stainless-steel shims at the movable bearing, the span was lifted to remove the load cells and lowered onto the bearings.

After releasing the U-span, the underbridge was moved backward over the new span. Finally, the span carrier was moved backward to release the front trolley onto the new span to allow the carrier to drive back to the casting yard.

Fig. 7: Launching of underbridge clears the span lowering area

In-Place Casting of the Continuous Spans

The 31,5 m U-spans were too short to cross Brenner Highway A22, the Rivers Secchia and Panaro and the new railway plants for the Modena West Interconnection. Nine 136 m long three-span continuous bridges were therefore cast in place. Although these bridges adopted the single-track U-section of the precast spans for esthetic continuity, the negative moment from spans of 40, 56, and 40 m required the use of taller webs at the piers.

Two movable scaffolding systems (MSS) and a ground-based modular falsework system were used to cast the 1310 m^3 continuous spans in three 53,1, 57,4, and 25,5 m long pours. The main 1300 t MSS was comprised of two overhead square trusses suspending the outer form through bar hangers.[2] The 110 m long trusses carried a portal crane for handling of reinforcement and inner forms along the full length of the MSS (*Fig. 8*). Reinforcement and inner forms were lifted from either side of the casting cell and moved longitudinally into position. The portal crane had an inverted L-frame with pinned leg to cope with gauge irregularities as a result of differential lateral deflections in the main girders of the MSS.

Fig. 8: Main MSS over Brenner Highway

The main central section of the square truss comprised two inner paired trusses holding the anchorages of the form hangers and an outer stabilization truss that controlled out-of-plane buckling and supported the rails of the portal crane. One of the main trusses was interrupted at the ends of the casting cell and the second one was extended into launching noses on either side of the casting cell. Long noses were necessary to control overturning during launching and to assist the lifting areas at both ends of the casting cell with the portal crane.

The main truss modules were delivered from Germany ready for lifting while the lighter launching noses were assembled on site before lifting. The main truss modules were spliced with large-diameter transverse pins for fast assembly while the launching noses were bolted.

Different types of modular support towers were used during assembly and dismantling of the unit in addition to the main support towers. The main towers were equipped with hydraulic support systems for the paired crossbeams that allowed flexural rotations at the support sections of the main trusses and lowered the trusses in one operation after application of prestressing to avoid overloading of form hangers. Longitudinal launching of the trusses was achieved with PTFE-based sledges and hydraulic long stroke cylinders acting into racks. Transverse shifting to the adjacent bridge alignment was achieved with the transverse hydraulic cylinders that were also used for geometry adjustment.

The outer form panels were assembled onto modular bottom frames. During suspension of the outer form modules, the bottom frames were progressively spliced to generate a stiff full-length horizontal truss that transferred the lateral loads applied to the forms to the front pier and the front cantilever of the completed bridge.

Upon suspension of the outer form and hydraulic adjustment of truss elevation, the camber was set by jacking the form hangers at the truss anchorages. Deflection analysis had to be particularly accurate to meet the tight geometry tolerances of HSR bridges. Structure–MSS interaction was analyzed during segment casting (*Fig. 9*), at the application of prestressing and during hydraulic lowering of the MSS. Calculated deflections of trusses and casting cell and tension in the form hangers were verified with load test before the first use of the unit by filling the casting cell with water.

Fig. 9: Casting cell of main MSS

After casting the segment and lowering the MSS, the portal crane was used to lower the outer form modules to the ground. The small number of segments to cast did not warrant full self-launching capabilities for the MSS. After launching the main trusses to the new span, the portal crane lifted the form modules back into position. The inner forms of the U-section were moved from the previous segment into the reinforcement cage of the new segment.

The first 53,1 m segment and the second 57,4 m segment of every three-span bridge were cast with three concrete pumps. One pump filled the bottom slab of the U-section from mid-span toward the rear pier, the second pump from mid-span toward the front pier, and the third pump filled the front cantilever. This sequence was studied to load the more deformable sections of the casting cell before concrete, which was retarded by 5 to 7 h, started to set. The difference in concrete elevation in the two webs was kept less than 0,5 m to control transverse load unbalance on the inner form. After casting the three segments of the superstructure, the main girders were moved back to the casting location for the second segment and shifted transversely to the support towers of the adjacent bridge. Casting two adjacent, three-span superstructures took on average 4 months.

Independent design checking included longitudinal launching and transverse shifting of the main trusses, structure–MSS interaction in the three casting configurations, and operations of the portal crane. Robustness (availability and stability of alternative load paths in case of buckling of primary load-carrying members) was assessed with nonlinear dynamic analysis.[3] Deflection analysis for the three casting configurations included trusses and hydraulic support systems.

A simpler custom-designed 800 t MSS was used for the Secchia Viaduct. Two light overhead box girders jacked to the casting elevation and lowered onto rollers prior to launching were used instead of 3D trusses. Support towers and suspended casting cell were assembled with modular components. This MSS did not have a portal crane. Deflection analysis was more complex for this unit due to the inelastic deformations of the great number of bolted connections. Difficult to predict deflections are a typical weak point of these modular assemblies. Also this MSS was load tested before the first use by filling the casting cell with water and the inner forms.

A modular ground-supported falsework was used for the Modena West Interconnection Bridges. Also this formwork was load tested due to its modular assembly nature.

Staged construction of the continuous spans made it necessary to lock-in stresses to minimize long-term deflections in the bridges, since vertical geometry is a critical issue for HSR bridges. A crossbeam fixed to the cantilevering front end of the first and second pour and diagonal stress bars anchored to the footing allowed to increase the negative moment in the front support section of the completed bridge to a magnitude similar to one pour casting. The force in the stress bars was monitored in real-time with load cells. Locked-in stresses were applied only to the bridges cast on falsework. With both types of MSS, the rear support of the unit was placed onto the front cantilever of the previous pour and its location was the tweel to achieve the right amount of negative bending at the support sections.

Fig. 10: Modena Viaduct

The QA/QC Qualification Process

The QA/QC qualification process for plants and processes was particularly complex in this project (*Fig. 10*). Batching plant, precasting facility, span carriers, self-launching underbridges with motorized support saddles, two MSSs for in-place casting of continuous spans, and a three-span pile-based falsework were all custom designed. In addition to the presence of innovative aspects in most components of the construction process, the interaction of so many innovations was also a reason of concern.

The QA/QC qualification process was based on three milestones: (a) analysis of Means-and-Methods, risk analysis/mitigation and definition of detailed step-by-step procedures (inclusive of contingency plans) for every major construction activity, (b) performance requirements, technical specifications and design criteria for every major component of special construction equipment, and (c) independent design checking of major construction equipment and load testing before use.

The QA/QC procedures for construction activities defined sequences of actions, interferences with parallel operations, possible unforeseen events, and authorized remedial actions, geometry tolerances, checks to perform, and actions to take in case of nonconformities.

The QA/QC procedures for special construction equipment defined performance requirements, technical specifications, design criteria, analysis methods and level of detail, and checks/tests to be performed on materials and during fabrication and site assembly. Equipment was fabricated under QA/QC and subjected to independent design checking and load testing after site assembly. Welding was certified by third parties. Commissioning of special construction equipment and testing of operations included casting full-scale sections of precast and cast-in-place U-spans.

Conclusions

Full-span precasting of 755 simply supported spans and in-place casting of 9 three-span continuous bridges allowed construction of 24,8 km of prestressed concrete HSR bridges in 30 months under global warranty on time, cost, and quality.

Accurate initial planning, frequent replanning and high levels of QA/QC are typical features of complex large-scale projects. Risk analysis/mitigation and QA/QC also include special construction equipment. The higher costs of high-quality equipment are for sure an issue, but the impacts of low-quality equipment can be catastrophic. Special construction equipment plays a critical role at these levels of industrialization.

Acknowledgements

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The author, as technology consultant of the prime contractor, wrote the QA/QC specs for bridge construction and the performance requirements, technical specs, and design criteria for all special bridge construction machines. As independent design checker of these machines, the author would like to thank Ing. Dante Sangalli and the technical offices of Alpi, Comtec, Deal, Hünnebeck, Röro-Thyssenkrupp, Sercam, and SPIC for the great work done under so tight deadlines. Last but for sure not least, the author would like to gratefully thank Impresa Pizzarotti & C. for authorizing the publication of this information.

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