Constructability as Design Objective

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Paper prepared for the session 'Infrastructure & Asset Management'
2024 Transportation Association of Canada (TAC) Conference & Exhibition
Vancouver, British Columbia

Photo of the Deh Cho Bridge by Dennis Hicks

Abstract

Bridge construction is a challenging engineering discipline which requires a good understanding of technology and structural behaviour. Generally, superstructure type, material, weight, availability of equipment, technical know-how, local conditions, schedule, and much more influence the means and methods of bridge construction. Especially for major and complex bridges, the choice of a cost-effective and reliable erection method as well as a diligent construction engineering approach are paramount for success. But even standard bridges require utmost attention in this regard because each situation is somehow different.

As several factors influence bridge constructability, it is of importance that a cost-effective and reliable erection method is developed in the conceptual design stage, rather than in the construction stage where most design parameters are effectively locked-in. Adjusting bridge design parameters at the construction stage due to constructability concerns can result in significant costs and delays. Conversely, considering constructability at the design stage prevents cost and schedule overruns, and yields synergistic efficiency gains by jointly addressing constructability and limit state requirements.

Via case studies of three complex steel bridge projects, this paper will demonstrate the importance of constructability as a design objective. It describes how the aspect of constructability was implemented in the design phases to confirm that the following construction phases could be executed without costly revisions and delays. In all three situations, the overarching goal was to capitalize on synergy effects and efficiency without compromising safety, structural integrity, and durability. Hereby, design and construction reliability was achieved by addressing constructability as a design objective.

Introduction

The construction of a bridge’s superstructure is often the most critical stage because the structural system is only partially complete and the assumed safety factors are much smaller compared to the final bridge structure and its service conditions. For probabilistic and economic reasons, the factored live and wind load forces for construction stages are often smaller than for the bridge in service. The same applies to seismic forces during construction if the bridge is constructed in an active seismic zone.

Conceptual bridge designs often lack a well-developed construction sequence and constructability reviews although this aspect can be design-governing. Some designers consider the review of critical construction stages more as an afterthought than as an integral part of the design. Hereby, members, found deficient in a secondary verification process, are strengthened to pass the “constructability test” without paying great attention to deformations or failure mechanisms of vital load paths. This design philosophy may be acceptable for many bridges from a code and contract perspective, but it imposes a risk to the project if member strengthening is not the right solution.

To capitalize on synergy effects and develop an overall safe and economical bridge concept, a design with “Constructability as Design Objective” is recommended. Such a design philosophy requires designers to consider constructability as a fully integrated design aspect from the start. The conceptual design stage is a critical design phase because most relevant design parameters, such as materials, spans, superstructure type and depth, articulation scheme and structural system, are already defined and locked-in for further investigations. For instance, changing spans or the superstructure type at an advanced design stage has major impacts on design costs and delivery schedules.

Constructability reviews at early design stages will prevent derailing projects and support the design team with expert advice in the field of bridge construction. For Design-Build and P3-Projects, or other Alternative Project Delivery (APD) projects, where designers and construction experts are working together when developing concepts, the benefits of an integrated constructability design approach are visible. In contrast, the traditional Design-Bid-Build (DBB) delivery model is more prone to revisions if constructability is not an integral part of the design and review process.

"Constructability as Design Objective" highlights the need and the benefits of such an integrated design process that goes beyond the traditional design philosophy which only focuses on the final bridge structure to confirm its performance and leaves construction aspects to the contractors and their erection engineers. A well-planned and executed constructability design approach discusses different methods via a value engineering assignment and develops a risk matrix by comparing preferred solutions and their specific advantages and disadvantages. This requires an unbiased perspective, meaningful experience, and good knowledge about the site and the construction industry. This iterative process takes time, but it is an investment that pays high dividends if design and construction are seen as one part of a shared success story.

For instance, for remote locations or cold temperature regions different construction methods may be better suited than for interurban and mild-climate conditions. Access and availability of equipment can be another factor that influences the choice of a specific bridge construction method and may govern the design. Therefore, designers and construction experts shall study the project-specific circumstances, including supply chain constrains, material and labor costs, weather conditions, delivery routes and other relevant aspects that can negatively affect the project during construction.

In the following, this paper discusses projects with challenging construction conditions. Those projects all have in common that the design was significantly influenced by the way the bridge was envisioned to be constructed. Those assumptions were documented in the design drawings to allow others to understand the complexity of superstructure erection and the structurally validated sequence of construction. The description of a staged construction process via drawings and text was an essential part of the design delivery package to portray the envisioned erection method in detail and establish confidence about the constructability of the project.

199 Ramp Superstructure along the Golden Ears Bridge in Langley, British Columbia, Canada

The curved 199A viaduct is part of the $800 million Golden Ears Bridge project in Langley, British Columbia, Canada and was built in 2009. The viaduct is an off ramp providing direct access to an industrial area on the south side of the main bridge and the Trans-Canada-Highway. Because of the spans and the challenging double-curved geometry of the superstructure, a steel segmental box girder structure was selected for execution. For the erection, the progressive cantilever method was envisioned after a conventional plate girder design was found to require more steel and being challenging to erect.[1]

The steel portion of the 199A viaduct is a four-span continuous superstructure with spans of 65 m, 82 m, 66 m, and 55 m. The narrow structure carries only two lanes of highway traffic with small shoulders. The alignment in plan includes an S-curve with a minimum radius of 130 m in the main span. The 82-m long and superelevated main span (see Figure 1) crosses several railway tracks and the south approach viaduct of the Golden Ears Bridge. This challenging situation restricted crane access and the placement of temporary bents. The combination of limited crane access together with long spans required exceptionally heavy-duty crawler cranes when lifting larger pieces. More conventional mobile cranes that could only be placed outside the railway clearance envelope or on the newly constructed south approach viaduct were not able to lift the size of segments originally envisioned.

Figure 1. 199A Ramp superstructure erection via the progressive cantilever method

Source: Spannovation

Initially, the superstructure was envisioned as a composite three steel plate girder system with splices at the dead load zero moment points. A constructability review indicated that the missing lateral buckling stability of a curved plate girder ruled out a single girder lift while lifting longer segments with a stable three plate girder cross section was beyond reasonable crane capacities as mentioned before.

Moreover, the plate girder solution required heavy-duty cross-frames and a continuous bottom lateral bracing to achieve the necessary torsional stiffness and strength. For the plate girder option, the steel weight of the 268-m long bridge was estimated above 900 t or 3.36 t/m. A value engineering alternative using a composite single steel box girder superstructure with only two webs demonstrated that around 20% of structural steel could be saved when compared to the original three plate girder design, and that the savings easily would offset the higher fabrication costs of the proposed box girder alternative.

To minimize the steel tonnage, structurally efficient details were developed. Due to strain compatibility, the bottom flange interacts with the longitudinal and transverse stiffeners attached to the flange. Hereby, the transverse and longitudinal stiffeners act as an integrated structural part of the bottom flange and reduce the effective thickness of the flange. This principle is widely used for orthotropic decks, but efficiency and steel savings are even better if fatigue does not govern the design. European and Asian engineers have developed methods to compensate for the additional detailing and welding efforts. For example, they use plate bottom flange stiffeners following the curved geometry with a polygonal line and kinks at transverse stiffener locations. This eliminates the need of a second flange (stiffener top flange) which otherwise is required to stabilize a curved longitudinal stiffener in the transverse direction. This simplification reduces welding and associated distortion effects.

The fabrication of the bridge was outsourced to China. The superstructure was fabricated in fully welded and assembled box girder segments limited to 10 m length and 35 t weight for transportation reasons. A complete trial assembly of the structure was conducted at the fabricator's plant in China to ensure perfect fit of adjacent segments before the structure was disassembled and shipped to Canada. The much shorter main span segments (with only 3 m length) were assembled using the progressive cantilever method with the help of cranes positioned on the main line viaduct for the south cantilever portion and outside the railway envelope for the north cantilever portion. In contrast, the approach span segments were spliced together on the ground and then lifted into place with the help of temporary supports. In 2023, AASHTO and NSBA published the Steel Bridge Erection Guide Specification, a document that provides advice to bridge designers and erection engineers.[2] This document is an excellent resource for bridge designers and erection engineers when designing complex bridges.

But even for shorter bridges without geometric challenges, the trial assembly approach offers great advantages. On-site remedial work, such as reaming bolt holes, ordering new splice plates, or the exchange of bracing components, can be costly and time consuming, especially in remote locations. If components are forced into position with brute force to overcome geometry shortcomings, the structure may experience deformations and stresses that were not accounted for in the analysis. For the segmentally erected curved steel box girder of the 199A ramp superstructure, the fabrication process was designed to avoid misfits and overstressed components. Prefabricated pieces of each segment (flanges and webs) were welded together using the neighbor segment as a template to achieve a perfect match, a process that follows the match-casting method developed for segmental concrete box girders.[3]

As predicted in the value engineering assignment, the final tonnage achieved 20% overall steel savings. To verify superstructure constructability, the bridge was analyzed for all erection stages to address concerns about girder instability during extreme cantilever stages and the deck casting sequence, but the superior structural behavior of the box girder (when compared to plate girders) required no additional strengthening. In this context, it is important to note that the selected progressive cantilever construction method which started from both main span piers must consider the steel box girder dead load moments of the cantilevers in the final bridge design because they are frozen into the structural system when the main span closure is made. The same applies to the camber values for the naked steel girder. Without investigating the critical construction stages and knowing the dead load moments, it would be impossible to take those effects into account when analyzing the completed bridge for relevant SLS and ULS scenarios. This is another important reason why designers should pay attention to the aspect of constructability in the design phases.

Deh Cho Bridge near Fort Providence, Northwest Territories, Canada

The Deh Cho Bridge is the first bridge structure crossing the Mackenzie, Canada's longest river. When the bridge opened in November 2012, it permanently replaced ferry and ice road services along Highway 3 connecting Yellowknife in the Northwest Territories with Highway 1 in the South. The bridge's remote location in the Canadian North with severe winter conditions of up to -40 °C required meticulous planning of all construction stages to achieve design reliability and construction efficiency.[4]

The symmetrical superstructure of the Deh Cho Bridge consists of two vertical Warren trusses which are connected by Chevron cross frames and wind bracings at top and bottom chord levels. This adaptation of an "open" steel box girder is designed to carry two lanes of traffic while acting compositely with an 11.3-m wide and 235-mm thick precast concrete deck. The new joint-less superstructure (from abutment to abutment) has a span arrangement of 90 m – 3 x 112.5 m – 190 m (navigation channel) – 3 x 112.5 m – 90 m with a total length of 1,045 m. The 190 m long main span is cable assisted allowing a constant superstructure depth of only 4.5 m over the entire length of the bridge (see Figure 2). This corresponds to a maximum slenderness value of 42 (span to depth ratio).

Figure 2. Deh Cho Bridge during construction

Photo by Arc Rajtar

The eight piers of the Deh Cho Bridge are founded on concrete spread footings which are cast into the Mackenzie Riverbed using cofferdams. Each pier consists of a lower solid concrete cone (reinforced with an outer steel shell protecting the concrete against ice forces) and an upper hollow steel head. The steel head has a base, two inclined legs, and a horizontal tie-beam connecting the tips of the legs. The lower concrete cone and the steel head are connected at the pier's bottleneck. Post-tensioned high-strength bars ensure that the critical connection stays tight and sealed under service loads.

Two steel A-pylons located at the tallest piers flank the navigation channel located in the bridge center. Each A-pylon is supported by two spherical bearings that allow a pendulum movement of the pylon in longitudinal bridge direction. Four groups of three stays each, arranged in two cable planes, are anchored at each pylon head using cast steel sockets with pin connections. The stays (locked coil cables with 100 mm diameter) are anchored at the third points of the main span and at the centers of the back spans using steel truss outrigger systems.

The articulation scheme utilizes disk bearings at the piers and abutments. The bearings guide the superstructure in the transverse bridge direction but allow longitudinal movements due to temperature changes. Pier 4 North (one of the main span piers) is the only location where the superstructure is longitudinally restrained. At the remaining piers, except the piers nearest to each abutment, Lock-up Devices (LUD or shock transmission units) are employed. The Lock-up Devices allow temperature displacements without generating noteworthy restraining effects, but for longitudinal impact forces due to gusty winds or braking loads, the devices rigidly connect the superstructure to the piers and permit load sharing between engaged piers.[5]

Figure 3. Deh Cho Bridge cable installation and superstructure launching

Photo by Bill Braden

The special site conditions, especially the low temperatures and the remote location, led to a design that minimizes field activities through maximum shop prefabrication (see Figure 3). This principle has been applied to most bridge components. Only abutments, curbs, and wearing surface have been designed for conventional construction methods. Incremental launching was determined as the most effective and economical superstructure erection method. This technique reduces the contractor's risk and accelerates construction progress when compared to other methods such as the span-by-span erection scheme or the balanced cantilever technique.

A high degree of prefabrication typically requires a careful consideration of transportation as well as onsite storage and construction aspects. The location of the bridge site and potential fabrication shops as well as possible access routes, transportation limitations and traffic restrictions were considered. It was decided to design all prefabricated components in such a manner that shipment via road and rail is possible. Standard transportation means were utilized to avoid oversized loads and special permits which increase costs. Fabrication of steel and precast concrete followed the industry's preferred methods allowing a high degree of repetition and an effective assembly-line fabrication process. Both principles are beneficial from a cost, schedule, and quality perspective, especially when many identical or similar pieces are produced.

Because of the bridge's remote location and the short periods of reasonable construction conditions, it was essential to minimize quality issues that require specialized repair techniques in the field. Therefore, it was decided to enforce a rigorous shop trial assembly combined with a thorough quality control (QC) and quality assurance (QA) process for all superstructure and pylon steel work. Extra time and cost for those activities were compensated by an increased onsite construction speed and cost savings as delays due to field repair work are minimized. Steel trial assembly is addressed by the Canadian Highway Bridge Design Code CAN/CSA-S6 and should reflect camber, alignment, accuracy of holes as well as fit-up of welded joints and milled surfaces.[6]

Figure 4. Deh Cho Bridge deck panel installation via work bridge placed on the truss

Photo by Bill Braden

The Deh Cho Bridge truss members have been optimized for structural performance. Cross sections of chords, diagonals, and posts have been carefully designed to use steel material as efficient as possible by combining structural requirements during construction and service. For instance, truss bottom chords have been particularly designed to accommodate the incremental launching erection method with its meaningful support reactions along the entire length of the truss bottom chord. Local bending and shear as well as lateral guiding effects combined with global demands (derived from a detailed investigation of a staged erection sequence) were included in the design of the superstructure. This fine tuning led to an optimized bottom chord cross section which does not require any extra material to satisfy the anticipated launching stages. High strength steel (485 MPa yield strength) was locally utilized to keep truss chord cross sections and superstructure depth constant over the entire bridge length. At piers, the chord cross sections have been boxed. This helped to control stresses and buckling effects.

In 2023, one stay cable of the Deh Cho Bridge snapped due to a wind-induced fatigue problem in the turnbuckle. It appeared that this failure was triggered by an initial flaw in the surface of the critical turnbuckle element which initiated the crack which then over time propagated deeper into the cross section because of the energy that was fed into the system by wind-induced cable oscillations. The failure mechanism in the critical cross section can be described as a High-Cycle Fatigue (HCF) problem which is characterized by a low stress amplitude in combination with a high frequency of stress cycles.

The bridge is designed to withstand the sudden loss of one cable as per PTI Recommendations[7], including the dynamic impact resulting from the sudden release of energy stored in the tensioned cable. In the context of “Constructability as Design Objective”, the design of the Deh Cho Bridge explicitly considered the possibility of cable replacement via maintenance instructions and design drawings that were part of the final design delivery package. For instance, the lower cable anchorages are equipped with steel brackets which are designed to connect a temporary destressing/stressing system. This jacking system allows to bypass the primary load path to remove the pin in the clevis connection when replacing the cable.

Canal Lachine Bridge in Montréal, Québec, Canada

The Canal Lachine Bridge is the new signature structure in downtown Montréal, Québec, Canada (see Figure 5). The curved cable-supported bridge is the center piece of the $1.5 billion Design-Build Turcot Project. The 350-m long structure was built in stages to accommodate the overall project construction schedule and facilitate traffic during construction. Delivered within the fast-paced Design-Build environment, the design required close collaboration between designer, contractor, architect, suppliers, fabricator, and owner.[8]

Figure 5. Canal Lachine Bridge in the colors of the Montreal Canadians

Source: Ministry of Transportation, Quebec

The 50-m wide superstructure carries two independent carriageways with a total of six traffic lanes. The main span utilizes a tower and single plane semi-fan arrangement of stays to support the 88-m long main span over the Lachine canal. The unique design had to accommodate building one carriageway to carry traffic for two years without cable supports before the second carriageway could be erected. Both halves are tied together at the lower cable anchorages and the pylon location after composite action was established. In this final configuration, they form a unique, highly redundant composite steel grillage system that achieves both efficiency and elegance. This innovative extradosed bridge utilizes multiple steel box girders connected by cross frames and transverse tie-beams to create a single superstructure type. Composite action is achieved using slender full-depth precast deck panels to accelerate construction. The continuous superstructure is fully isolated from the substructure to control seismic design forces on substructure elements and their foundations. This allowed single columns and mono-pile foundations.

The footprint of the old bridge covered a substantial section of the new bridge. To maintain traffic during construction, a phased construction sequence was a mandatory requirement. In fact, the partially completed northbound superstructure had to carry public traffic before the old bridge could be completely removed and the southbound structure be built (see Figure 6). Accordingly, the contractor’s preferred construction sequence had to be developed and implemented into the final design of the bridge. Because of Montréal's cold winters, it was desired to maximize prefabrication as well as minimize cast-in-place concrete and field welding operations. The use of full-depth precast deck panels in combination with cast-in-place closure pours was the preferred construction method to quickly build a reliable composite concrete deck. Bolted field splices were the preferred connections for the steel superstructure and pylon segments.

Figure 6. Canal Lachine Bridge partially erected and already commissioned to service

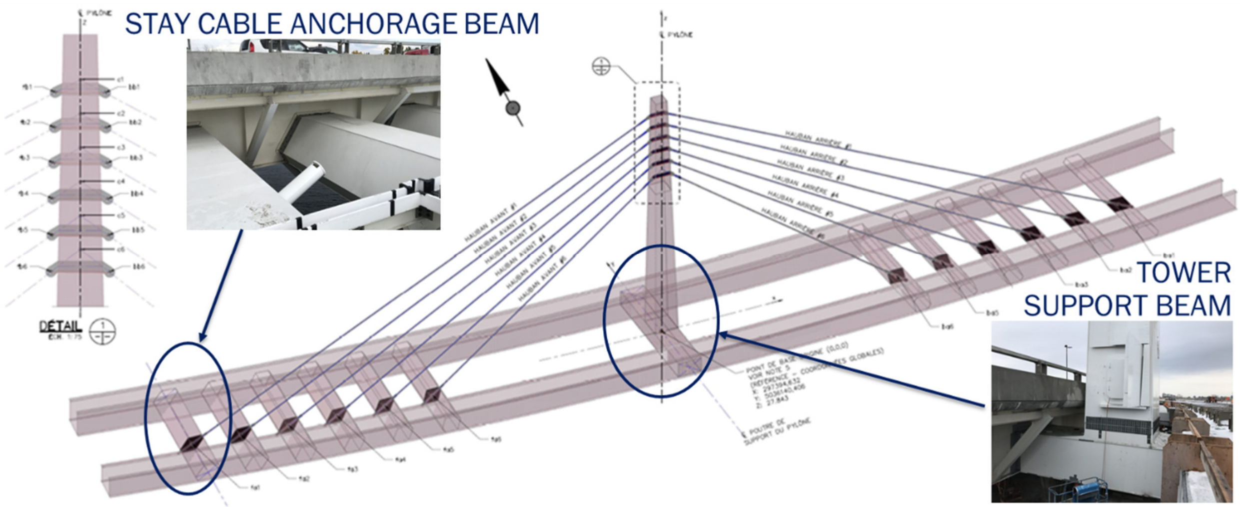
Source: KPH Turcot

For the Canal Lachine Bridge, the discussed challenges have been seen as opportunities that promote innovation. For instance, the modified articulation scheme using isolation bearings permitted a superstructure type that combines structural efficiency with modern elegance. This new fully isolated concept sets the structure apart from most cable supported bridges. It is the first curved extradosed bridge with a composite superstructure type that utilizes multiple coupled box girders.

Replacing a major piece of aging infrastructure with a complex signature bridge in a congested urban environment is a challenge par excellence, particularly if public traffic must remain in service during construction. Consideration of appropriate Accelerated Bridge Construction (ABC) techniques and a staged construction approach in the early design stage led to an innovative superstructure type that could be built as two independent structures with traffic permitted on the first half while the second half was still under construction. By adding the fourth dimension of bridge engineering (the timeline of construction) to the conceptual bridge design phase, a new type of superstructure was developed and verified far before the results from the final design process and erection engineering were available.

The two superstructure halves are tied together with thirteen tie-beams in the main and back spans (see Figure 7). The tie-beams are also box girders and part of the extradosed system by acting as a stay anchorage beam or pylon support beam. Besides this primary function, the tie-beams work as external diaphragms between both carriageways redistributing vertical loads and minimizing live load deflections. They participate as well in sharing horizontal forces in longitudinal and transverse bridge direction by activating a frame system between the two superstructure halves. In contrast to one fully closed superstructure concept, the developed solution with tie-beams permits a gap between the two carriageways so that natural light can flow into the space below. Light and rain will allow vegetation to grow and help to rebuild the natural habitat under this 50-m wide bridge.

Figure 7. Canal Lachine Bridge stay system with the integrated superstructure framing system



Source: Parsons

The staged superstructure erection sequence using multiple small steel box girder segments was specifically chosen to simplify the transport and erection of segments and accommodate traffic during construction. As such, the northbound structure was designed to be a freestanding steel composite box girder system in the temporary configuration although at this stage one pier of the old bridge still penetrated the deck and interrupted the continuity of one of the three box girders carrying the northbound carriageway. The unusual and highly skewed support condition at Axis 3 (tower support location) with only three columns is adequate to support the final structure but not for the temporary condition with only one carriageway built and in operation. Two temporary supports (one for each superstructure half) using the two friction-pendulum test bearings were adopted to solve this challenge.

After the design was completed and contracts with the subcontractors were signed, the joint venture partners' design and construction teams worked closely with the erector and its engineer to facilitate the temporary support design. The temporary supports were constructed about 25 mm higher than required to provide flexibility for the installation of the tower support beam and a controlled activation of the permanent bearing below the tower. Critical to the 100% design delivery was feedback from the fabricators regarding details or alternatives that would allow to optimize fabrication regarding cost and schedule. Each change presented a challenge for the design team. Therefore, change requests were evaluated against cost, design, and schedule impacts. Through this review it was determined that a few design detail changes to the longitudinal stiffeners, vertical web stiffeners, and a greater use of bolted connections over welded connections would result in a more constructible and economic design.

Stiffeners always create fabrication challenges that can negatively influence steel production and consequently also affect price and schedule. As such, the use of longitudinal stiffeners was scrutinized during the final design phase after the fabricator was selected. Once fabricator input was received, it was clear that there was a preference for fewer and stronger longitudinal stiffeners. This was attributed to the higher labor costs associated with cutting, fitting, and welding of longitudinal stiffeners which were evaluated against simply increasing the corresponding plate thickness for stiffeners and the bottom flange. Another modification was requested based on the fabricator's fabrication and transportation plan. Therefore, the final design package included locations for optional field splices should the fabricator wish to breakdown the structure into differently sized segments.

Conclusions

Construction staging and erection engineering are critical tasks for complex bridges and require a thorough investigation and review during all stages of design. Erection engineers are inclined to push the structure to permitted limits. Therefore, erection engineering involves meaningful knowledge about structural behaviour, the various erection techniques, processes, and state-of-the-art equipment and technologies. Since bridge construction has no margin for error, realization often directly depends on the feasibility of proven and accepted construction methods. For that reason, bridge designers need to envision feasible construction stages and understand associated schedule and budget implications.

Cost efficient bridge designs are often solutions that utilize synergy effects by concurrently addressing relevant construction stages and code prescribed serviceability and ultimate limit states. As in the presented case studies, such synergistic solutions range from the inherent modification of the shape and/or material properties of key structural members (to account for site conditions and erection techniques) to designing components with the goal to leverage prefabrication as best suited on a case-by-case basis. Such holistic solutions demand the consideration of constructability as a design objective from the conceptual design phase when the entire process is envisioned, developed, and verified. The added consideration of constructability yields significant savings for owners and contractors, and facilitates the construction of functional yet elegant pieces of critical infrastructure.

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