Design and Construction of the Deh Cho Bridge
Challenges, Innovation, and Opportunities

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Paper prepared for presentation
at the "Bridges – Innovations" Session

of the 2012 Conference of the
Transportation Association of Canada
Fredericton, New Brunswick

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Keywords

Extradosed Bridge System; Value Engineering; Assembly-line Design Approach; Conceptual Bridge Design; Failure Mechanism Concept; Fuse Design Philosophy; Fast-tracked Erection Methods; Ecological Light-weight Design Principals; Optimization of Structural Performance.

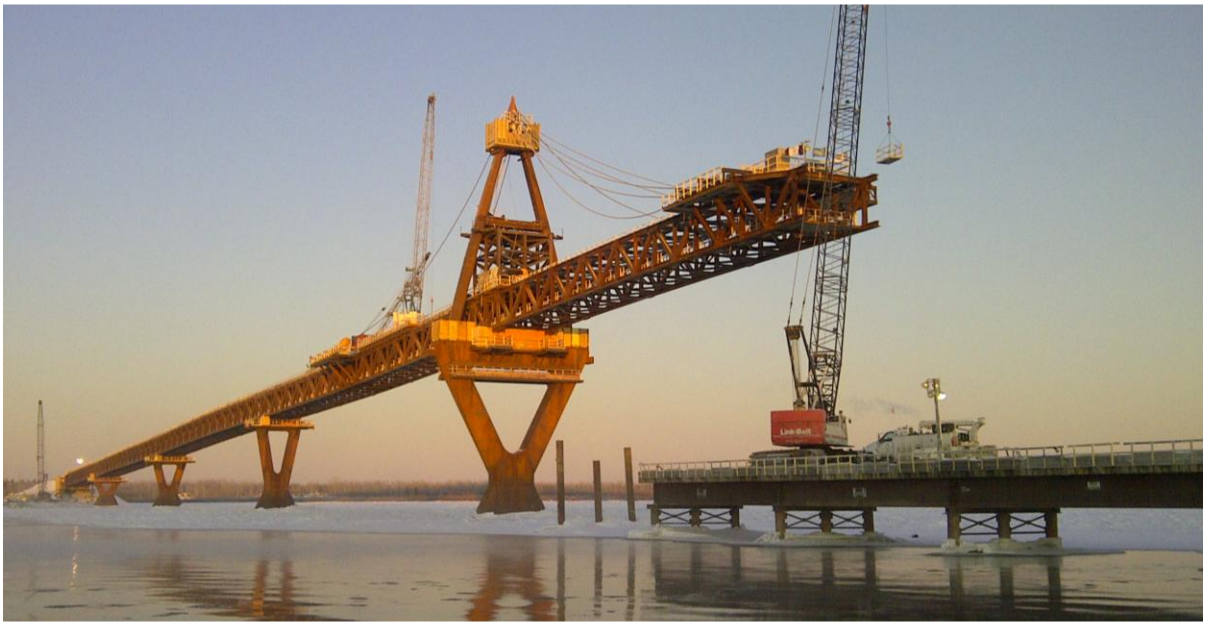

Fig. 1: Deh Cho Bridge under construction (Photo: Dennis Hicks, Associated Engineering)

Abstract

The Deh Cho Bridge will be the first bridge structure crossing the Mackenzie, Canada's longest river. When the bridge is opened it will permanently replace 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 North with severe winter conditions of up to -40 °C requires meticulous planning and is an extraordinary challenge for men and equipment (see Figure 1).

Innovative design methods led to the design of a unique 1045 m long continuous cable supported superstructure with expansion joints only at the abutments. The design employs ecological light-weight design principles as well as fast-tracked fabrication and erection methods. Structural performance of the superstructure has been optimized for construction and service scenarios allowing a high degree of repetition as well as aesthetic proportions and rhythm.

Serious design challenges often require new philosophies and strategies. On the other hand, they provide exceptional opportunities for innovation. The Assembly-line Design Approach, the Failure Mechanism Concept, and the Fuse Design Philosophy have been specifically developed for the Deh Cho Bridge with the purpose to cope with extraordinary schedule and design requirements.

Fig. 2: Rendering of the Deh Cho Bridge near Fort Providence (Infinity)

1. Introduction

The Deh Cho Bridge near Fort Providence is the largest bridge project ever undertaken in the Northwest Territories (see Figure 2). Construction of the bridge is now in full swing after steel fabrication was halted in 2008 when superstructure design and construction deficiencies were discovered by an independent review team. In spring 2009 Infinity Engineering Group (Infinity) was retained by the design coordinator Sargent & Associates to develop a new superstructure design complying with the project requirements and compatible with the substructure that had already been built in the river. The redesign was completed in a compressed design schedule of six months. Superstructure fabrication started in early 2010. The bridge is predicted to open in late 2012.

2. Design Features

The symmetrical superstructure 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 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 (see Figure 3). 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. This corresponds to a maximum slenderness value of 42 (span to depth ratio).

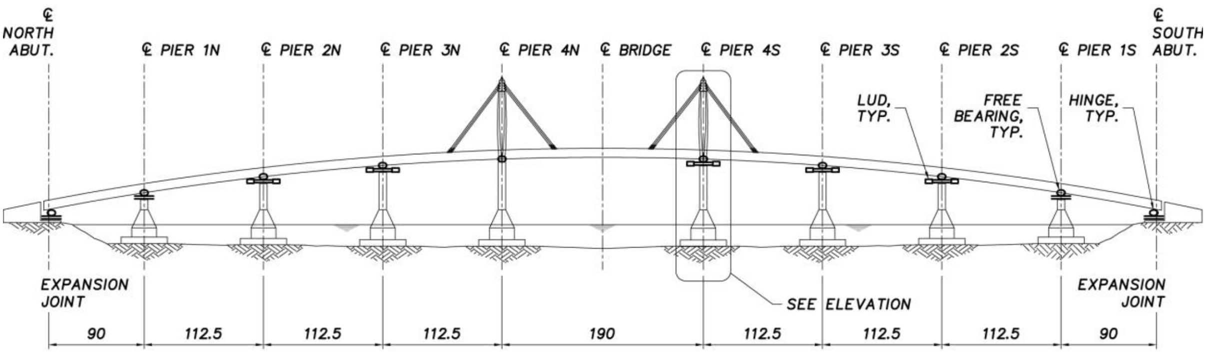

Fig. 3: Span arrangement and articulation scheme (Infinity)

The articulation scheme (see Figure 3) 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 (see Figure 4, Elevation). 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.

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 (see Figure 4, Elevation). 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 centres of the back spans using steel truss outrigger systems.

The eight piers of the Deh Cho Bridge are founded on concrete spread footings which are cast into the Mackenzie River bed 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 steel head. The steel head has a base, two inclined legs, and a tie-beam connecting the legs. The lower concrete cone and the steel head are connected at the pier's bottle-neck (called the Pier Connection Detail). Post-tensioned high-strength bars ensure that the critical connection stays tight and sealed for service loads.

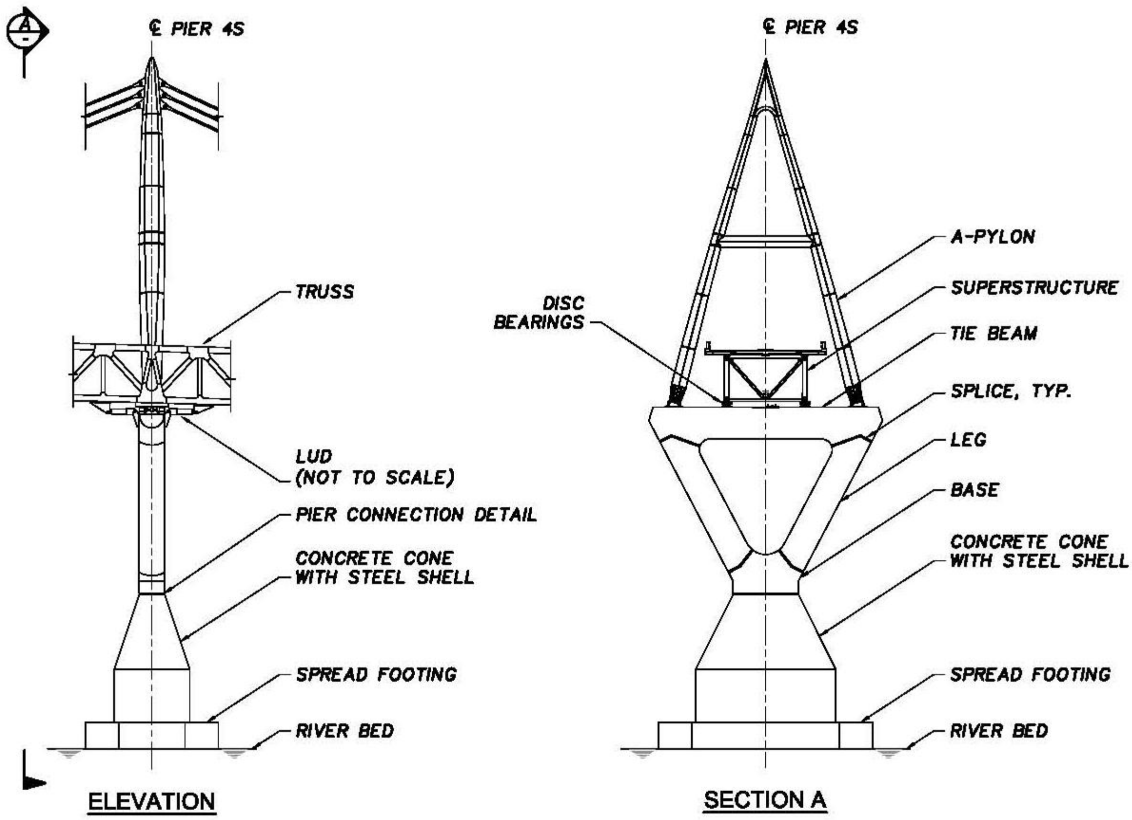

Fig. 4: Pier 4 South with A-pylon and superstructure (Infinity)

The Deh Cho Bridge can be classified as an Extradosed Bridge System. [1, 2, 3] Similar to conventional extradosed concrete box girders the "open" steel box girder has significant bending stiffness and is only locally reinforced with stays and "king posts". As such, the Deh Cho Bridge has a very different structural behaviour than similar looking cable-stayed bridges which typically do not require stiffening girders due to their multi-stay configuration in combination with anchor cables. [4, 5]

3. Challenges

3.1 Site

The extreme temperature conditions at the bridge site of up to -40 °C permit reasonable construction conditions only during short periods between June and December. Ice breakup occurs between April and May and requires full removal of any works supported by temporary foundations in the river (see Figure 5). Material delivery to the North shore depends on ferry or ice road service since no alternative route is available. Between ice road closure and ice breakup no river crossings via truck are possible. For those reasons erection stages along the critical path had to be carefully planned and executed.

3.2 Design

For complex bridges, it is good design practice to investigate and present at least one feasible erection method as part of the design. This is imperative for major bridges with extraordinary site conditions because an economical fabrication, transportation and construction scheme typically governs the design. Based on economy, the following five aspects were identified as the most critical design parameters for the Deh Cho Bridge: (1) Site conditions, (2) Erection method, (3) Transportation aspects, (4) Fabrication preferences, and (5) Shop trial assembly.

Fig. 5: Piers 3N and 4N with temporary works during winter 2011/2012 (Photo: Arndt Becker, Infinity)

The special site conditions, especially the low temperatures and the remote location, led to a design that minimizes field activities through maximum shop prefabrication. 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 (see Figure 6). 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 aspects. The location of the bridge site and potential fabrication shops as well as possible access routes, transportation limitations and traffic restrictions have been 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.

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 (analogous to mass production in the car industry).

Because of the bridge's remote location and the short periods of reasonable construction conditions, it was essential to minimize quality issues that require repair 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 are compensated by faster onsite construction speed and 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.

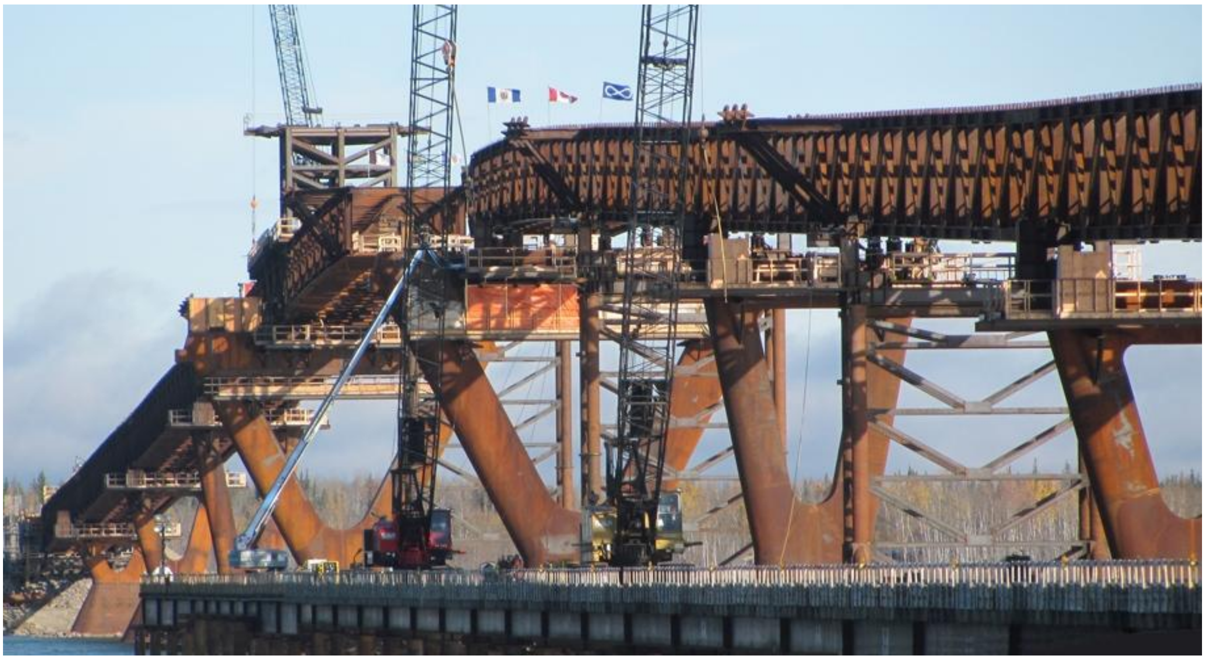

Fig. 6: Truss launching utilizing temporary bents (Photo: Dennis Hicks, Associated Engineering)

3.3 Budget

In order to meet the budget the new design for the superstructure had to consider economical design principles as well as cost effective fabrication and erection methods. To verify the economy of the newly proposed superstructure concept a value engineering assignment was conducted.

"Value Engineering uses a combination of creative and analytical techniques to identify alternative ways to achieve objectives." [6] As such value engineering is an important task often conducted for major bridges to ensure that the selected design is a viable solution meeting design criteria and budget. During a typical value engineering process different bridge proposals are analysed, discussed, and evaluated by experienced engineers who identify and weigh considerable technical and financial aspects. For instance, material quantities are a characteristic and measurable evaluation criterion. Other aspects such as construction cost, risk, and schedule or durability, adaptability, inspection and maintenance requirements may be considered as well but are difficult to quantify.

Infinity conducted a value engineering assignment for the Deh Cho Bridge superstructure by comparing the original with a newly developed design optimized for structural performance (see chapter 4.4). [7] The result clearly showed that the new superstructure design would permit significant material savings of more than 20% for structural steel and up to 30% for deck concrete. More importantly designer (Infinity) and reviewers (T.Y. Lin International, URS Corporation, and BPTEC-DNW Engineering) confirmed that the new design meets the design criteria and allows superstructure launching. Because of the budget constraints and other significant advantages (e.g. lower expected maintenance costs) it was decided to abandon the original design and realize Infinity's superstructure design.

3.4 Schedule

The new superstructure design task had to be performed in a timely manner to avoid further delays and extra costs. Infinity agreed to deliver a fully designed, checked, and reviewed design within six months after receiving the notice to proceed. One of the greatest challenges was drafting. Over hundred of unique design drawings had to be prepared, checked, and reviewed following a rigorous QC and QA procedure before the design could be sealed, signed, and released as "Issued for Construction".

Key to success was a meticulously planned project management approach involving the entire design, drafting, and review team right from the start. Numerous internal and external face-to-face meetings were held to achieve agreement and approval as fast as possible during all critical design stages.

4. Innovation

4.1 Assembly-line Design Approach

Infinity's design scope included the following design items: (1) steel truss superstructure, (2) composite concrete deck, (3) stay system, (4) steel A-pylons, (5) deck sealing and asphalt wearing surface, (6) concrete curbs and steel railing, (7) bearings and Lock-up Devices, (8) expansion joints, (9) erection feasibility, and (10) superstructure/substructure compatibility.

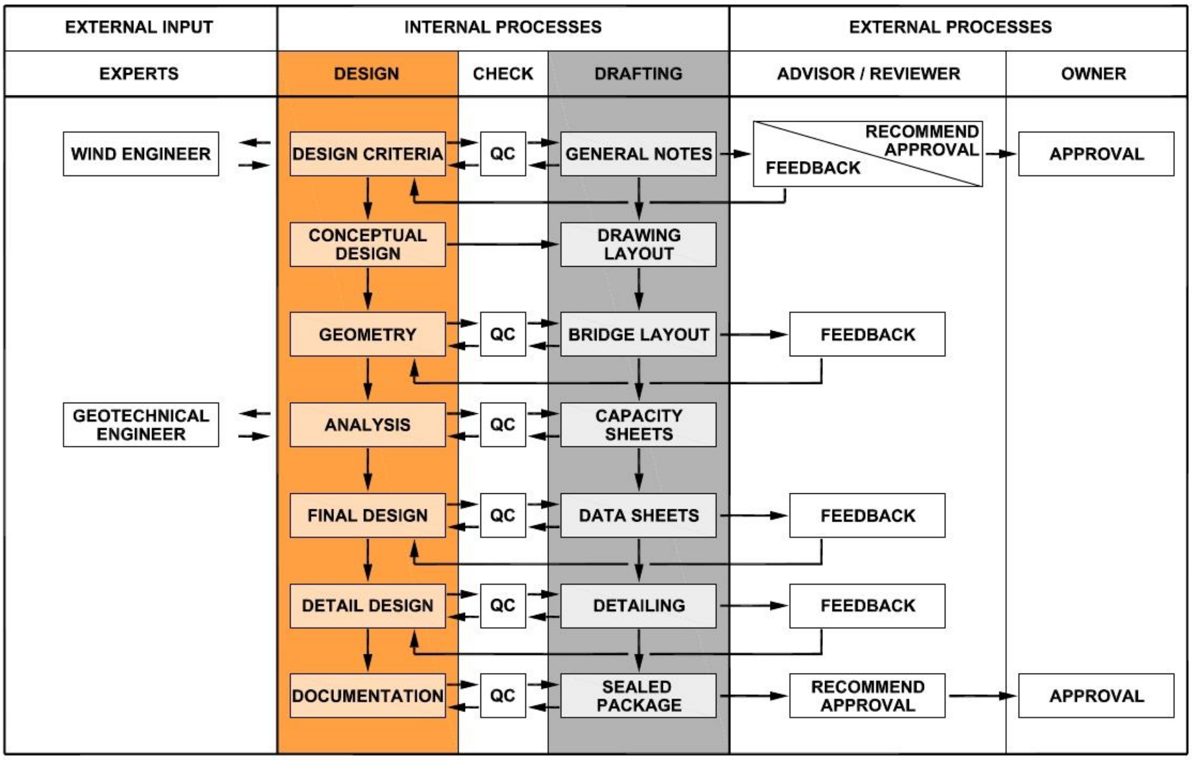

Fig. 7: Assembly-line Design Approach used for the Deh Cho Bridge (Infinity)

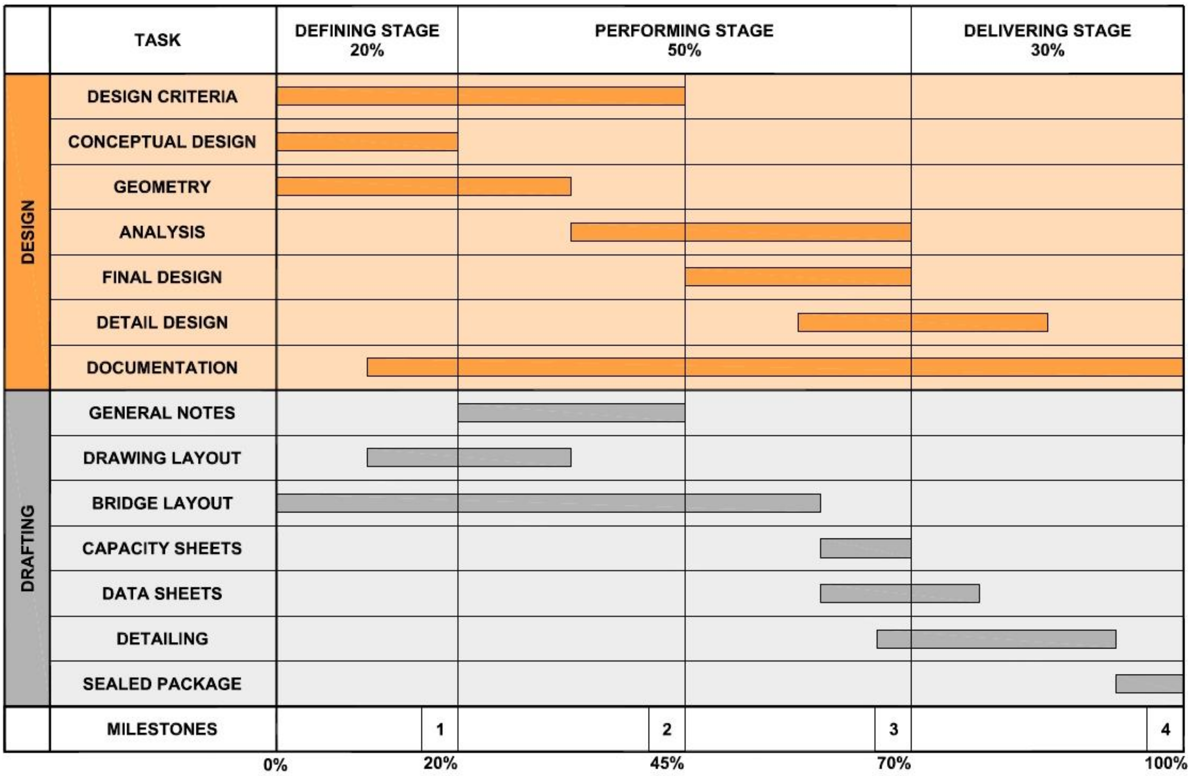

Fig. 8: Gantt chart picturing the Assembly-line Design Approach (Infinity)

The Assembly-line Design Approach is an evolved design strategy that significantly accelerates the design through the development of interdependent but individually treated design components (e.g. steel superstructure, concrete deck, stay system, A-pylons). Because of their interdependence, interfaces between design components must be given top priority. The lead designer identifies, develops, and documents critical interfaces and shares the information with the design team. Right from the beginning special emphasis must be laid on the compatibility of the individually executed design components. The definition of design components and their interfaces is a vital part of the conceptual bridge design phase and should be addressed immediately after the bridge concept is developed and approved (see chapter 4.2). This way many design and drafting tasks can be simultaneously executed without compromising quality (see Figures 7 and 8).

In the final set of sealed and signed design drawings (Sealed Package) each design component has its own chapter (analogous to a book). Drawings in each chapter strictly follow predefined hierarchy levels starting with very general content (lowest hierarchy level) to very complex details in shop drawing quality (highest hierarchy level). Cross references to other chapters and hierarchy levels within the same chapter are required but only permitted in the drawing notes that can be found on each drawing in the same corner.

As mentioned before drafting was identified as the most challenging design task along the critical path because its progress directly depends on the outcome of all other design tasks. The Assembly-line Design Approach bypasses most tasks as far as possible and gets drafting started long before other important design tasks (e.g. Analysis and Final Design) are completed (see Figure 8). This has the following advantages: (1) Design Criteria, Geometry, and Drawing Layout are properly laid out, well documented right from the beginning, and continuously updated, (2) drafters directly support designers with relevant information (e.g. Geometry), and (3) early drawings are kept as simple and concise as possible enhancing familiarization and comprehension.

During the Delivering Stage the Assembly-line Design Approach allows drafting to focus on templates (Data Sheets to be filled with designers' specifications) and the task Detailing (see Figure 8). The predefined templates significantly reduce drafting work, permit quick revisions, improve transparency, and support QC.

4.2 Conceptual Bridge Design

The conceptual design phase is the most important design stage because key design decisions are made during this early stage. The lead designer focuses on the general concept and ensures that the newly developed design is feasible, complies with relevant design criteria, and satisfies the owner's expectations. Infinity defined for the conceptual design of Deh Cho Bridge superstructure the following priorities: (1) compatibility with the constructed piers, (2) proven fast-tracked fabrication and erection methods for the superstructure, (3) economic and ecological light-weight design principles, as well as (4) an inexpensive and reliable deck.

The compatibility with the existing piers was established using the Failure-Mechanism-Concept (see chapter 4.3). This innovative technique was developed for the Deh Cho Bridge and used to verify that the 1045 m long superstructure could be built as a single continuous unit with expansion joints only at the abutments. As a result, two complex and costly expansion joints originally proposed for the 190 m long main span of the bridge were eliminated.

For erection of the steel superstructure the incremental launching method was selected. Consequently, cross sections of the steel truss were designed to optimize the structure's performance during launching and service [8]. The structural depth of the truss and its chords was kept uniform over the entire bridge length allowing a high degree of repetition during design, fabrication and erection as well as respecting aesthetic proportions and rhythm.

Light-weight design principles were thoroughly employed minimizing mass of structural members and saving resources. Generally trusses and cable supported structures have been used over centuries by bridge engineers in order to reduce dead load and material. [9, 10, 11] However, the consequent application of light-weight design principles for the Deh Cho Bridge led to an innovative composite extradosed truss bridge that has not much in common with post-tensioned extradosed concrete box girders designed by French and Japanese engineers in the last century. [1]

The concrete deck of the Deh Cho Bridge has an average thickness of only 235 mm (see Figure 9). This light-weight deck was achieved using two-way action and the yield-line theory for the Ultimate Limit State. [12] Upper truss chords and floor beams between chords act compositely together with the deck slab creating a very efficient structural system for the governing local wheel and axle loads. The cantilevering deck portions are strengthened by structurally integrated cast-in-place concrete curbs which serve as edge beams redistributing wheel loads. These largely forgotten design principles, widely used by François Hennebique (1842-1921) and Eduard Züblin (1850-1916) for their "cassette slabs", allow designing extremely efficient concrete slabs reinforced with mild steel only. [13, 14]

Fig. 9: Precast deck panels stored onsite (Photo: Arndt Becker, Infinity)

4.3 Failure Mechanism Concept

The I-35 Mississippi River Bridge in Minneapolis, Minnesota, USA [15] and the Boulevard De La Concorde Overpass in Laval, Quebec, Canada [16] are regrettable examples of sudden bridge collapses causing the loss of human lives. We are convinced that those unpredicted incidents are avoidable when the consequences of critical failure mechanisms are investigated and appropriately addressed during the design phase.

The design philosophy of the Failure Mechanism Concept (FMC) goes beyond the traditional Ultimate Limit State design approach adopted by modern codes. [17, 18] In addition to modern code requirements the FMC focuses on the weakest sections along primary load paths. A primary load path is hereby defined as the structure's preferred way of resisting loads. The objective of the concept is the development of a structure that announces a serious problem long before a fatal chain reaction is triggered.

Structural integrity and redundancy are fundamental principles when applying the FMC. The entire structure (foundations, abutments, piers, superstructure, etc) shall be considered as a whole. This new view point will provide designers with valuable information about probable failure mechanisms and the structure's ultimate behaviour when reaching its structural capacity. Unpredicted failures along primary load paths shall be avoided by deliberately defining weak sections. The predefined weak sections shall act as fuses allowing significant deformations and the activation of redundant load paths long before the structure forfeits its structural resistance. The so called Fuse Design Philosophy is the "backbone" of the FMC; noticeable deformations shall be triggered so that the structure's critical condition can be recognized before lives are endangered and the investment is put at risk. [19]

The FMC has been developed for the Deh Cho Bridge during the conceptual design phase to allow a continuous superstructure over the entire bridge length. The basic problem was to accommodate temperature movements with the necessity to absorb longitudinal forces such as wind, earthquake, and braking loads. The piers had been identified with such a stiff behaviour that only one pier could be equipped with longitudinally fixed bearings. Other piers required sliding bearings to allow temperature movements in a nearly unrestrained manner. This meant that a traditional articulation scheme would rely only on one pier to provide longitudinal stability of the 1045 m long superstructure. None of the piers had enough capacity to satisfy this requirement alone. Therefore, it was decided to employ Lock-up Devices which allow load sharing between piers for dynamically applied loads but do not restrain slow acting temperature movements occurring over a relative long period of time.

Consequently, it was recognized that the weakest pier section, the pier bottleneck (see Figure 3, Elevation, Pier Connection Detail), would form an excellent fuse. If designed properly with a ductile failure mechanism (providing sufficient rotational capacity) the fuse would allow the engagement of Lock-up Devices installed at other piers. This way additional redundant load paths could be activated before the capacity of the single pier with fixed bearings is exhausted. Therefore, the degree of pre-stress in the Pier Connection Detail (fuse section) was chosen as low as possible (for safety reasons) but high enough to avoid decompression during service (for durability reasons).

4.4 Optimization of Structural Performance

Construction stages are critical for bridges and require investigation. Erection engineers are inclined to push the structure to permitted limits. Erection engineering involves much knowledge about various erection techniques, processes, and state-of-the-art equipment.

Fig. 10: Truss supported by the tallest temporary bent in the main span (Photo: Arndt Becker, Infinity)

Realization often directly depends on the feasibility of proven and accepted construction techniques. For that reason, bridge designers require an excellent understanding of available construction techniques to ensure their designs will endure envisioned construction stages without increasing the construction budget.

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. Plastic design methods (such as the yield-line theory, the Failure Mechanism Concept or the Fuse Design Philosophy) are very helpful in pushing the limits without compromising safety and quality. In other words, plastic design principles allow an optimization of structural performance for construction and final conditions. This in turn means significant savings for owners and contractors.

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 (see Figure 10). For instance, truss bottom chords have been particularly designed to accommodate the incremental launching erection method. Local bending and shear as well as lateral guiding effects combined with global demands (derived from a detailed investigation of a staged erection sequence) have been included. This fine tuning led to an optimized cross section which does not require any extra material to satisfy anticipated launching stages. High strength steel (485 MPa yield strength) has been 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.

5. Opportunities

5.1 Design

The design of the Deh Cho Bridge had to deal with many unique problems directly related to the remote site and the extreme weather conditions. However, these extraordinary circumstances offered excellent opportunities to design the structure in an innovative way leading to the development of new techniques in bridge design and construction. From this viewpoint the Deh Cho Bridge is one of the few engineering achievements that promote new design philosophies avoiding unpredictable collapses, enhancing durability, and achieving higher returns on investment.

5.2 Fabrication

Fabrication of the 1045 m long superstructure was performed under enormous time pressure. One of the design priorities was to focus on a fast-tracked fabrication method. The Lego™ system realized by the designer for truss fabrication allowed the fabricator to produce segments using the assembly-line fabrication method for shop processes and during trial assembly. Up to six shops were simultaneously employed before pieces were trial assembled in Quebec, Canada. In average one truss segment per week (55 segments total) was delivered to site. Launching of the North approach commenced after one third of the superstructure was fabricated.

5.3 Erection

Onsite erection followed the same principles of mass production. Repetition and prefabrication significantly helped the contractor to standardize erection methods, processes, and onsite QC. The high degree of prefabrication allowed construction to proceed even in harsh winter conditions although construction speed was reduced. For example, installation of twelve fully assembled locked coil cables was performed at -25 °C with a team of four specialists in only three weeks (see Figure 11).

Fig. 11: Cable installation with ferry “Merv Hardie” in the background (Photo: Chad Amiel, Infinity)

5.4 Investment

The cost of a new vehicle is not just the price tag on the dashboard. The same is true for bridges. Inspection, maintenance, and repair require additional funds that can easily triple the construction cost over the life span of the structure. Even more funds are required when for various reasons the design service life cannot be achieved and an early replacement is required. For that reason, designers and owners must consider the overall return on investment. This is particularly true for major bridges because they are often paid by generations to come. Adaptability, durability, robustness, inspection, and maintenance need to be carefully considered because replacement of a major bridge cannot be achieved overnight (neither technically nor financially).

The Deh Cho Bridge follows best design practices by addressing those points. For example, a comprehensive maintenance manual has been developed for the entire bridge. A system similar to a car inspection and maintenance program will help the owner and its inspectors to recognize potential deficiencies in an early state so that progressive deterioration and costly repairs can be avoided. This customized and systematic effort of reducing maintenance cost and extending service life is an attempt to increase the overall return on investment for the Deh Cho Bridge and bridges in general.

6. Conclusions

Bridges like the Deh Cho Bridge are “lighthouses of our engineering discipline”. They mirror the never ending desire of mankind to overcome obstacles of any nature. But the Deh Cho Bridge is more; it is a meaningful investment and an outstanding opportunity to prove that modern progress in an industrialized society is possible in a responsible manner and in harmony with Canada’s Aboriginal people and Mother Nature.

Fig. 12:”Lighthouse of the bridge engineering discipline” (Photo: Arc Rajtar, Levelton)

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