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A sophisticated, iterative analytical approach to re-evaluating the bridge superstructure has put this project on the path to completion.

Fast-Tracked BridgeDesign

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CROSSING THE MACKENZIE RIVER in Canada'a Northwest Territories is anything but easy. In summer a ferry provides a way across, and in winter passage is via an ice bridge. But during the transition seasons, as the ice is breaking up or before it freezes solid, neither option is available.

The Deh Cho Bridge now being constructed soon will provide a permanent link for ground transportation in the area. It is a composite steel truss bridge with a cable assisted main span. The structural system can be classified as a composite bridge with hybrid extradosed-cable stayed features. Comparable to a cable stayed system, the primary purpose of the cables is to support the truss in spanning the navigation channel. Cable stayed bridges use a close stay spacing to realize slender superstructures. However, contrary to a cable stayed system, the backstays on the Deh Cho Bridge are not anchored at a pier location. The backstays function by activating the bending stiffness of the truss similar to an extradosed system. This reveals the difference of an extradosed bridge and a classical cable stayed bridge in terms of the structural system.

The two-lane, nine-span bridge has main navigation span of 623 ft. The approach spans are symmetrical about the center of the bridge. Each end begins with a 295-ft span followed by three 369-ft spans. The total length of the bridge is 3,427 ft. The superstructure consists of two 15-ft deep Warren trusses with a transverse spacing of 24 ft and a 9-in-thick precast composite deck.

The truss members are built-up I-sections. Two A-shaped pylons, located at Pier IV South and Pier IV North, each support two cable planes. Each cable plane consists of six cables connected to the main truss through an outrigger system. Figure 1 shows the bridge layout.

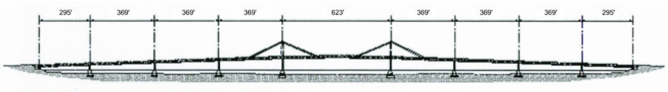


Figure 1: General arrangement of the Deh Cho Bridge includes nine spans from 295 ft to 623 ft in length.

The Deh Cho bridge will provide a year-round means for crossing the Mackenzie River in Canada's Northwest Territories where until now access has been seasonally interrupted.

Design

The design philosophy adopted for the Deh Cho Bridge consists of the *big picture approach*, the *failure mechanism concept*, and the *integrity rule*.

In adopting a *big picture* approach for the design of the Deh Cho Bridge, special consideration was given to functionality, safety, durability, constructability, cost, maintenance and aesthetics. Member profiles and materials were selected for their efficiency in resisting the primary force effects they experience. As an example, the bottom chord is an optimized I-profile resisting axial demands during service and in addition bending during launching. The dead load to payload ratio is minimized through the principles of lightweight design. The primary structural objective was to tune the system to be flexible for temperature effects while at the same time being stiff for live and wind loads.

The *failure mechanism* concept was applied to ensure that the structure does not experience a sudden collapse under any given load scenarios. The primary load paths are designed for a controlled failure mechanism. The load travels through a series of structural components comparable to a structural chain. The weakest link in the chain is determined by the designer and engineered to fail with adequate warning (ductile behaviour).

The Post-Tensioning Institute (PTI) recommends that designers consider cable loss scenarios. For those extreme events the designer should ensure the *integrity* of the bridge is not endangered. Basically, the design engineer should have a clear understanding of the load path and load behaviour for various load combinations. In absence of a secondary load path, it is important to design the weakest member along the path with a ductile behaviour to signal an overload through visual deformations or at least partial damage prior to collapse. For example, the cable anchorage and attachments are designed for the minimum breaking load of the cable, making the cables the crucial component of this particular load path.

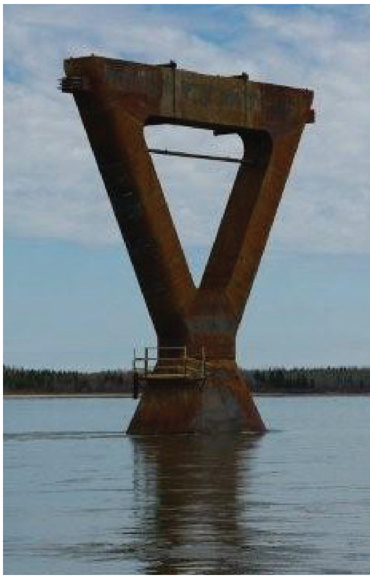
Value Engineered Design

The principles of lightweight design led to a saving of 25% in the use of structural steel. The deck consist of precast concrete

Proceeding With the New Design

Construction work on a major bridge crossing the Mackenzie River in Canada's Northwest Territories is again in full swing after being temporarily halted for an extensive redesign of the steel superstructure. The $180 million (Canadian) crossing will provide a permanent connection across the river for the communities of Yellowknife and Ft. Providence to the lower highway system of Canada.

An independent review by T.Y. Lin International (TYLin) on behalf of the owner identified deficiencies in the original superstructure design. Infinity Engineering Group Ltd. was retained to propose conceptual solutions to eliminate the inadequacies with the original design. Infinity developed a redesign option for an extradosed steel truss bridge, the first of its kind in North America. A value engineering exercise showed this approach would result in significant savings in cost and schedule while simultaneously improving safety, durability, and constructability. In January 2010, Infinity completed the redesign in an accelerated six-month schedule that allowed the project to proceed.



Above right: A steel-armored reinforced concrete base in the Mackenzie River awaits erection of one of the Deh Cho Bridge's two A-shaped cable support towers. Photo: GNWT

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panels with cast-in-place infills. A combination of a waterproofing membrane with two layers of asphalt is applied to the surface for sealing purposes. The new deck is designed as a four-way slab resting on the truss and floor beams, thereby cutting the concrete mass by 30% and eliminating the need for pre-stressing.

The articulation scheme allows a continuous deck for the entire length of the superstructure, which eliminated the need for two modular deck joints on the bridge. The articulation scheme involves the use of modern lock-up devices, which act like shock absorbers to allow slow acting movements while restraining sudden force effects.

Compact locked coil cables have been used for the stay system using a Galfan coating and cast sockets. The cables will be shipped to site in the final length but the adjustable anchorage at the superstructure allows for length variations to correct and manipulate cable forces. Compared to common strands, locked coil cables are slender with compact anchorage details. The condition of the outer wires and anchorages can be easily inspected visually. The locations of the cable anchorages were selected for improved structural and aesthetic behaviour. The simplified anchorages can be easily inspected and maintained.

Constructability aspects as well as a lightweight design approach have been adopted for the design of the superstructure and pylons. The design of the bridge incorporates a proven construction scheme.

A truss is an excellent candidate for lightweight design as it predominantly relies on compression and tension members to transfer loads. Making the trusses composite with the concrete bridge deck uses both elements to economic advantage. The principles of lightweight design require maximization of the payload to dead load ratio. This is achieved by minimizing the self weight of the bridge, primarily the concrete deck. In the case of the Deh Cho Bridge, the high live load factors and the dynamic load allowance of the Canadian Highway Bridge Design Code govern the concrete slab design. An average slab thickness of 8½ in. has been realized using Yield Line Theory.

Continuous Superstructure

A continuous superstructure avoids the use of expansion joints on the bridge and reduces the service and maintenance effort. The design objective of the deck was to engineer a continuous system over the entire bridge length. To achieve the goal the articulation scheme was required to allow temperature movements with minimal restraining effects and "lock-up" the movements during fast-acting load effects such as wind gusts in order to share the loads with several piers. The so-called lock-up devices (LUDs) mounted between superstructure and pier enable this articulation scheme. These devices are dampers with restrictive orifices; they only allow a significant translation when a certain force is applied over a period of several hours.

Constructability

The truss was engineered as a "Lego'"system that is easy to fabricate and assemble. The chord member geometry was kept constant throughout the length of the bridge. The varying force effects were resisted through changing the steel strength and when necessary by boxing of the chord "I" section through the addition of side plates. Steel Grades of 350 AT and 485 AT have been specified for the truss. Open profiles were selected for the truss members for good access and assembly.

Analysis

The analysis undertaken for the project included: a global analysis of the entire bridge, an erection staging analysis and local finite element analyses for specific connections and details. For the global analysis of the bridge on LARSA 4D, a 3D model was created that included the entire bridge consisting of foundations, piers and abutments, bearings, truss, pylons, cables and deck. The salient features of the analysis are briefly described in this section.

Cable Tuning

The first step in the global analysis was to tune the dead load sharing in the truss and the cables to obtain a beneficial behaviour. An accurate estimate of the cable force was obtained by making all the members infinitely stiff under dead load. The preliminary cable size was determined using the dead load cable force and a contingency for transitory loads. The properties of the cables thus determined were used in the model together with the real stiffness of all other members, compensating for the cable elongation by using a temperature load case.

Negative Camber

The span arrangement of the Deh Cho Bridge requires a truss camber at the cable support locations. The span supported by the back stays is only 112.5 m while the span supported by the front stays is 190 m. This uneven configuration results in unbalanced cable forces in the front and back stays, and thus causes a tower rotation to find equilibrium (see Figure 2). Because the back stays are not connected to a fixed point such as an anchor pier, typical for cable-stayed bridges, truss uplift at the backspan cable support cannot be compensated for by cable force manipulation.

To achieve the given roadway profile the truss needed to be cambered down (negative camber) in the backspan. The truss camber for half the bridge is shown in Figure 3.

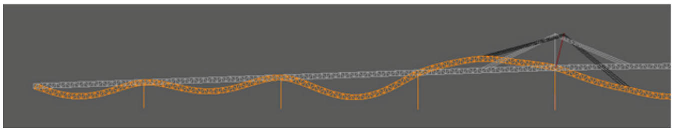

Figure 2: Unbalanced system with dead load and cable tensioning applied.

The truss camber shown in Figure 3 compensates for the permanent load deflections shown in Figure 2, resulting in the desired roadway profile (see Figure 4).

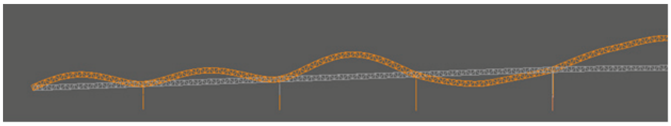

Figure 3: The truss camber in the backspan helps compensate for the uplift introduced on that span due to the unbalanced cable stay load.

Influence Surfaces

Influence surfaces were used to determine the maximum force effects from moving loads. An influence surface, or 3D grid of influence coefficients, is created by running a unit load over a predefined load area (typically traffic lanes). An influence surface can be generated for a force effect (i.e. bending, shear, compression etc.) at any cross section of a component of the structure. The magnitude of the force effect from a vehicle placed anywhere on the load area is determined from the influence coefficients and the vehicle loads.

Ultimately, the vehicle is positioned on the influence surface to maximize the force effects under consideration. The influence surface for the bottom chord in the center of hanging span can be seen in Figure 5. The corresponding deformation for a truck positioned in the most unfavourable location is shown in Figure 6.

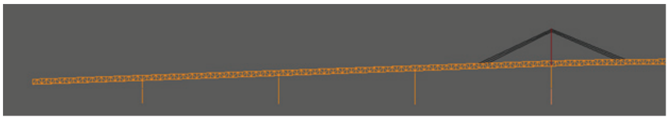

Figure 4: With the camber, cable shortening and dead load applied, the bridge deck profile is as planned.

Unique Articulation

Two separate models were created to represent the different articulation scenarios depending on the nature of horizontal load effects. The bridge is fixed transversely at the piers and abutments. The continuous superstructure requires both flexibility for movements and fixity for load sharing of longitudinal loads. This contradiction has been resolved by the use of LUDs that release temperature restraining effects but engage the piers for external load effects such as wind and braking loads.

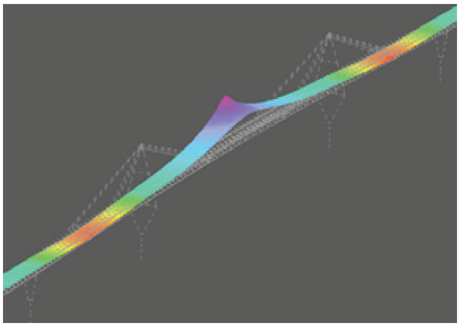

Figure 5: Influence surfaces for individual component members are generated by analyzing the effect of moving loads at various positions on the structure.

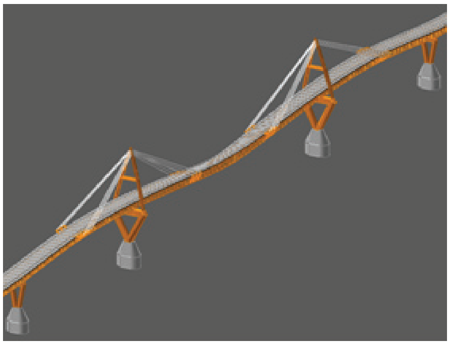

Figure 6: The model shows the bridge deformation due to placing the movable load at the position where it has the most significant effect.

The master-slave joint feature of the software was used to model the articulation. The use of master-slave joints provides the option to couple or uncouple any of the six degrees of freedom to model various articulation conditions. In the end the bridge is fixed longitudinally for temperature load effects only at one main pier. The use of LUDs has enabled a seamless deck for the entire length of the bridge.

Erection Analysis

For the Deh Cho Bridge the following erection stages have been incorporated into the design:

- Launching 1,621-ft-long truss approaches from each abutment
- Installation of A-pylons and cables

- One-step stressing of all cables simultaneously by lowering truss at Pier 4
- Deck panel installation up to Pier 4
- Installation of 187-ft-long lifting span
- Deck panel installation in the main span
- Activation of composite action
- Casting curb and installation of railing
- Installation of waterproofing and wearing surface

A staged analysis for the launch was performed. The effect of camber was included in the analysis using a temperature load case. This method has the advantage of being able to turn camber off when the truss is moved ahead and connected to the supports in the new location. About 130 launch stages were analysed and summarized in demand envelopes. A typical stage is shown in Figure 7.

After erection of the A-pylon is completed, the truss is jacked up at Pier 4 to facilitate installation of the cables. Thereafter, the truss is lowered to its final position stressing all cables simultaneously, as shown in Figure 8.

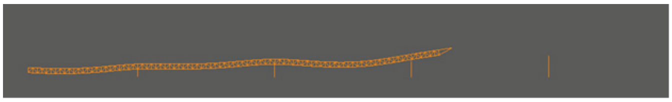

Figure 7: One of more that 130 launch stages analyzed in developing the construction plan.

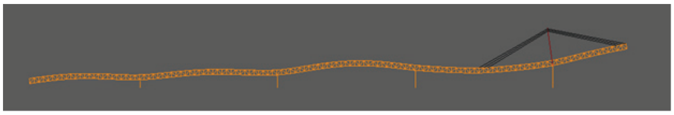

Figure 8: The cables are stressed in one step, but do not at that point take up the camber in the span adjacent to the main span.

Figure 9: The lifting span operation results in a load balance that brings the bridge structure close to its final constructed profile.

The lifting span splice requires geometric compatibility of the truss ends (see Figure 9). This is achieved by loading the backspan through placing deck panels from the abutment to Pier 4. The design takes into account the construction demands including forces, deflections and rotations from the stages before.

Conclusion

The Deh Cho Bridge redesign is a unique example of an engineering assignment that involved a complex long-span bridge on a highly accelerated design schedule with considerable technical, project management and quality reviews. Rigorous analysis was conducted for cable tuning and camber, live load and other transitory loads. In addition, the staged analysis was conducted for the construction scheme. This investigation consisted of truss launching, cable stressing and a lifting span operation.

The principles of lightweight design were applied to value engineer the bridge. The redesign significantly simplified and improved the constructability of the bridge in addition to achieving an estimated 25% savings in structural steel. One of the major innovative features of the design is a continuous superstructure over the entire length of the bridge, making it the longest jointless bridge, from abutment to abutment, in North America. The submission of the issued for construction drawings earlier this year has enabled this project to move forward toward an anticipated completion in November 2011. MSC

Owner

Government of Northwest Territories

Territorial Advisors

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Engineer of Record

Infinity Engineering Group Ltd., North Vancouver, British Columbia, Canada (AISC Member)

Peer Reviewer

URS Corporation, Tampa, Fla. (AISC Member)

Steel Fabricator

Canam Steel Corporation, St. Gedeon de Beauce, Quebec and Point of Rocks, Md. (AISC and NSBA Member)

Structural Analysis Software

Larsa 4D