The Basohli Cable Stayed Bridge, India

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ABSTRACT: The Basohli Bridge is a new cable stayed bridge over the River Ravi in Jammu-Kashmir, India that is being procured under the Design-Build delivery system for the owner, Border Roads Organization. Construction commenced in June 2011 and has an expected completion date in early 2014. The contract bidding documents included a base concept cable stayed bridge; however, the successful team opted to develop an alternate concept that utilized a hybrid concrete and steel system that focused on minimizing construction duration and cost.

The presentation will discuss the development of the bridge and also present various aspects of detailed design. The presentation will focus on optimizing a cable stayed bridge for this specific site, including evaluating the aerodynamic stability of the narrow bridge in a moderate wind zone. Furthermore, design challenges associated with the Indian design codes will be discussed.

INTRODUCTION

The Basohli Bridge is a project over two decades in the making. For a long time, Indian officials have discussed the economic and strategic advantages such a crossing would have on Northern India. By connecting the states of Himachal Pradesh and Jammu & Kashmir, both tourism and commercial mining would rise and a strategic route would be provided for the flow of army troops in and out of insurgency prone regions. With the ever growing expansion which is currently taking place within the country, the Border Roads Organisation of the Ministry of Defence took control of the project and opted to tender the job using a design-bid-build delivery system. When bid prices came in at costs significantly exceeding those estimated, the project was not awarded. Instead, the project was later re-tendered using a design-build delivery system; a system never before used for a cable-stayed bridge in India.

A design-build delivery system shifts the responsibilities of design from the owner to the contractor and thus results in increased freedom for the contractor. However, in order to limit this freedom and ensure certain features are implemented into the design, the owner incorporated various project constraints into the contract. In this case, the original bid concept was included as an option and all alternative design concepts had to adhere to a number of restrictions. In reference to the original base concept, the span lengths and roadway widths could not be changed. In addition, the top of tower elevation, the top of footing elevation and the foundation founding levels had to remain at their prescribed values. These project constraints were further compounded by the site constraints, to be discussed in the following section, which together had a significant impact on the design process and system configuration.

For a cost of 1,450 million rupees, the project was awarded to a joint venture of IRCON and S.P.Singla Constructions Pvt. Ltd. which opted to bid an alternate cable-stayed concept aimed at improving constructability and reducing cost and duration. In order for the construction of the foundations to commence as planned, the design firms responsible for the winning bridge concept, Infinity Engineering in conjunction with ASC Infratech Pvt. Ltd., had to meet an aggressive design schedule of six months.

This paper describes the development of the design concept which was adopted for construction with emphasis placed towards aspects of the design which contribute towards the overall static and dynamic response of the bridge, as well as the construction scheme and schedule. In addition, several of the design issues which were faced are discussed in detail.

DESCRIPTION OF THE BRIDGE

PROJECT LOCATION AND SITE CONSTRAINTS - The bridge traverses the River Ravi, cutting across the boundary of Hamachal-Pradesh and Jammu & Kashmir states in the northwest corner of the country, adjacent to Pakistan (Figure 1). At high flow, the river extends to a width of nearly 300 meters and rises to levels just below its steep valley walls (Figure 2). The area surrounding the bridge site is composed mainly of rock, has a highly variable climate, and is considered a high seismic region with moderate wind speeds.

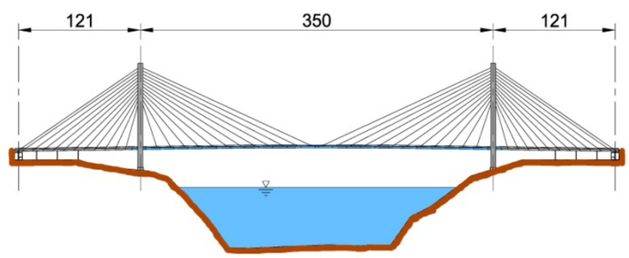
Figure 1 - Project Location

Figure 2 - Bridge Crossing Site Photo

Depending on the season, temperature fluctuations in the order of +/- 38°C can occur. Not far to the North-West is the boundary between the Eurasian and Indian tectonic plates which is renowned for its seismic activity; most recently the 2005 Kashmir earthquake which resulted in direct damage to roads and bridges estimated at over 20,000 million rupees [Durrani et al., 2005]. No active faults are known to extend through the bridge line and due to the geology of the site and the overall length of the bridge, large non-synchronous movements within the bridge limits is not expected.

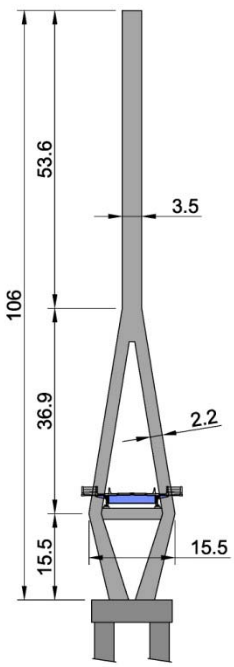
OVERALL LAYOUT - The span layout is symmetric (121m – 350m -121m), with pylons positioned at the top of the river banks (Figure 3). Two inclined cable planes splay outwards from each pylon in a semi-fan configuration, connecting to the superstructure at 14-meter spacing in the main span and 10.3 meters in the side spans. Near the abutments, three sets of intermediate piers spaced at just over 20 meters form a secondary support system. When complete, the bridge will accommodate two lanes of traffic as well as two footpaths.

Figure 3 - Span Configuration



PYLONS - Several different pylon configurations were evaluated during the bridge's development, including an A-frame and an inverted Y-shape, amongst others. However, the modified diamond configuration offered several advantages (Figure 4). With large seismic demands, it was considered prudent to reduce the transverse stiffness of the pylons while providing ductility so that energy could be effectively dissipated during a seismic event. An inverted Y-shaped pylon behaves similarly to a truss with large axial tension and compressions in the lower pylon legs under transverse seismic loading. With predominately axial demands, the inability to achieve adequate ductility or energy absorption into the pylon was deemed unacceptable. By reversing the inclination of the legs at deck level and bringing them together at the base, thereby forming a modified diamond shape, the seismic behaviour is changed from predominately axial demands to flexural which can be utilized for ductility and energy absorption. In addition, bringing the lower legs together reduces the footprint of the foundations.

Figure 4 -Pylon Geometry

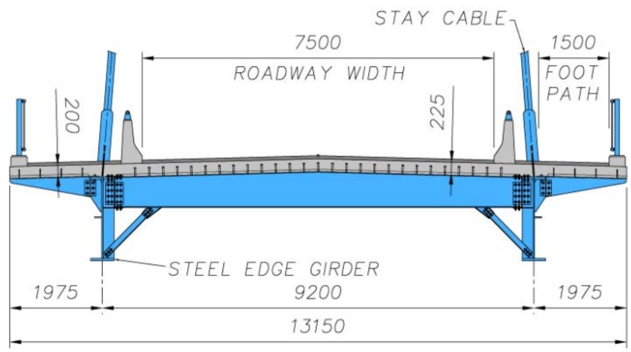


Above deck there were several perceived advantages to bringing the upper legs together as quick as reasonable. First, the single vertical portion of the pylon is simpler and faster to cast relative to the dual inclined legs. Second, the stay cables can be anchored completely within the vertical portion which simplifies construction and improves the aerodynamic performance of the superstructure, as will be discussed later.

To further simplify construction, each pylon was designed with a constant width of 5 meters for the full height. Additionally, the 48 cables at each pylon are anchored within the top 33 meters by utilizing steel anchor boxes which act compositely with the concrete walls.

SUPERSTRUCTURE - The superstructure has two edge girder lines at 9.2m centers supported by the two cable planes. The mainspan consists of a lightweight composite steel grid utilizing longitudinal edge girders with transverse floor beams for the roadway and cantilever steel brackets for the footpaths, spaced every 3.5 meters, all made composite with a concrete deck slab (Figure 5). Initially, the deck was designed with full depth pre-cast deck panels made composite with closure pours; however, during the design phase the contractor elected to revise the deck to fully cast-in-place. Switching of the deck system from precast to cast-in-place required a re-analysis of the bridge system to properly capture the time-dependent effects associated with a fully cast-in-place deck that experiences significantly more creep and shrinkage effects. The results showed a considerable redistribution of axial compression forces from the concrete deck to the steel grid due to the increased creep and shrinkage strains which resulted in a notable increase in the section properties of the main longitudinal girders.

Figure 5 - Mainspan Typical Section

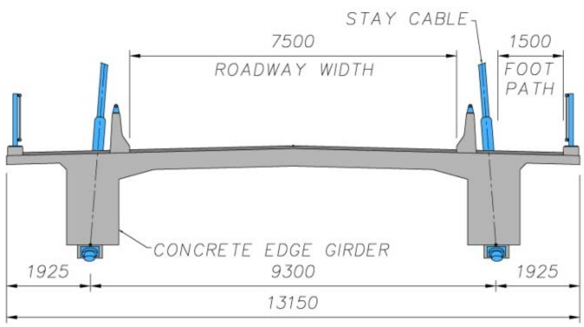


As stated previously, the span lengths could not be revised from the base concept; therefore, the alternative design was developed to accommodate sidespans that are less than optimal and represented only 34% of the mainspan length. Short sidespans have some advantages; however, the main challenge is providing sufficient mass to efficiently balance the much longer mainspan. To overcome this challenge, the Basohli Bridge employs a hybrid configuration where the sidespans are a relatively heavy concrete edge girder system which can balance the lighter composite steel mainspan system. Considering the existing ground line is relatively near the roadway elevation, the concrete sidespans are cast-in-place on falsework.

The sidespan superstructure utilizes a clear spanning deck slab between edge girders without transverse floorbeams, taking advantage of the narrow roadway to simplify forming. Additionally, the footpaths are simple cantilevers without transverse beams (Figure 6).

The last 6 meters of the superstructure at each abutment is cast as a full-depth solid diaphragm in order to provide additional mass to avoid uplift at the abutment bearings under service level loads. Under all service load combinations the bearings are not subjected to uplift forces; however, for factored or ultimate loads, the bearings would be subject to uplift. To accommodate this, hold-downs comprising of two spiral strand cables at each abutment connect the superstructure to the abutment so the mass of the abutment can be mobilized to resist the uplift. The hold-down cables are initially stressed and are detailed to allow the superstructure to translate and rotate longitudinally without creating unacceptable flexural demands on the cables. For long-term performance, each spiral strand cable is also detailed to be fully inspectable and replaceable.

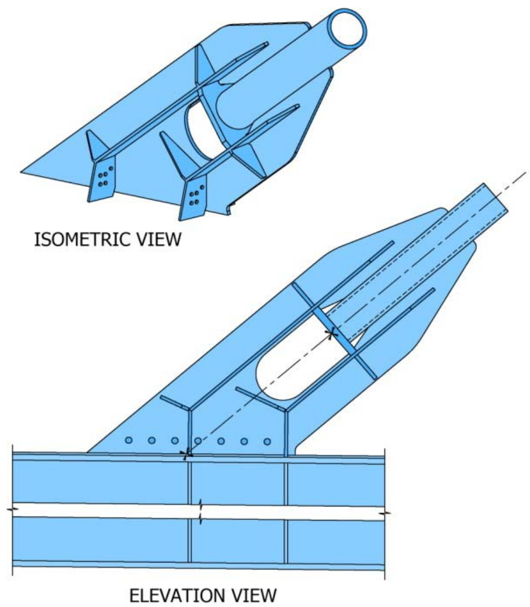
Figure 6 - Sidespan Typical Section



The hybrid superstructure also provides advantages in terms of construction duration by providing multiple work fronts and concurrent activities. As a result, the concrete side spans can be cast-in-place on falsework concurrently with the construction of the pylons; while in the interim, the mainspan steel components are being fabricated. After pylon construction has proceeded beyond the first few sets of cable anchorages and the side spans are complete, erection of the main span can commence in a progressive cantilever fashion using prefabricated steel elements. Using the progressive cantilever method with a previously completed side span has a significant advantage of adding stability to the system to resist wind buffeting loads during cantilevering. As such, supplemental tie-downs or counter weighting is not required.

With two different superstructure systems in use, two different stay anchorages had to be designed. In the side spans, the stay cables extend through the concrete edge girders and are anchored on the bottom soffit in concrete blisters. Conversely, in the mainspan, the stay cables are anchored above deck using a steel anchorage assembly that is welded directly to the web of the steel edge girders, providing a direct load path for the axial cable loads into the longitudinal girder system (Figure 7).

Figure 7 - Mainspan Cable Anchorage



INTERMEDIATE PIERS - Three sets of intermediate piers are provided in each side span to help stiffen the pylon and sidespan superstructure and reduce flexural demands from vertical wind and live load. The intermediate piers are installed after the bridge is complete and resist no permanent loads except for a minor amount of axial forces due to creep and shrinkage of the bridge. Intermediate piers are to be fabricated out of 400 millimeter diameter steel pipe with lengths ranging from 7.3 to 9.7 meters. In order to allow longitudinal movements and rotations of the bridge the intermediate piers are pin connected to the superstructure and footings. The anchorage brackets used to make the pin connection are post-tensioned with bars to both the footing cap and the superstructure edge girder. It should be noted that the intermediate piers provide no transverse stiffness to the system.

ARTICULATION AND BEARINGS - Vertically, the superstructure is supported by pot bearings at the pylons and abutments, and longitudinally the bridge is fixed at one pylon and allowed to move freely at all other substructure locations. The longitudinal fixity is provided through reinforced neoprene bearings placed between the superstructure deck slab and pylon. The expansion and contraction movements of the bridge are accommodated by modular expansion joints at both abutments.

Transversely, the bridge is restrained at both abutments and both pylons. At the abutments, a guided metal shear lock system is provided between the superstructure diaphragm and the abutment cap. At the pylons, lateral steel bearing plates are provided between the superstructure deck slab and the pylons. A small gap is provided between the embedded bearing plates that allows the superstructure to accommodate rotations and longitudinal movements of the system under transient loads, yet still provide a restraint to transverse loads. The tower transverse bearing plates were located and configured with care to provide easy access for inspection and replacement.

CABLES - In total there are 96 cables, the largest of which employs 29-15.7mm diameter seven wire strands, each individually greased and sheathed. In order to provide a secondary layer of corrosion protection, each cable is covered with an ungrouted high-density polyethylene (HDPE) pipe with double helical ribs to reduce the potential for unacceptable vibrations. The cables will be installed and stressed using the strand-by-strand method with the jacking operations occurring in the pylon.

CONSTRUCTION SEQUENCE - Construction of the bridge started with mobilization, site clearing and excavation in June 2011 and is expected to culminate in early 2014, well ahead of the contractual requirement. The sequencing for erection commences with the construction of the cast-in-place towers and side spans concurrently, or these activities can proceed independently of each other as desired. Upon completion, progressive cantilever construction of the mainspan commences and may begin before the pylon construction is completed. A typical mainspan segment cycle is described below:

01. Install a segment of steel edge girders and transverse floor-beams
02. Install associative side span stay cable and stress to initial force
03. Install associative mainspan stay cable and stress to initial force
04. Advance the cast-in-place deck forms
05. Install rebar, cast deck and cure
06. Stress associative main span stay cable to final force (2nd stressing)
07. Advance steel erection traveler

Once all main span segments are in place, a 2nd stressing is performed on most of the side span stays. This step was necessary to avoid overstressing the side spans and/or cracking of the concrete tower earlier in the sequence. Following the installation of the midspan closure segment, four sets of cables at the centre of the main span are slightly de-stressed in order to induce permanent compression into the deck at midspan through the generated positive moment. As a result, longitudinal post-tensioning, a somewhat common feature in cable-stayed bridge decks, is not required. After the entire deck is cast, the concrete barriers are installed and the wearing surface placed. The final major activity before service is to finish installation of the intermediate piers under the side spans.

DESIGN ISSUES

WIND LOADING - The Basohli Bridge at 13.15 meters wide can be classified as a very narrow structure relative to its 350 meter mainspan. Narrow and light weight cable supported bridges are dynamically sensitive structures prone to flutter instability issues; therefore, during development of the bridge, significant attention was placed on configuring a structure that would minimize the potential for adverse behavior under high wind events. First, to minimize the bluff-body effects at the leading edge, the main longitudinal girders were moved inwards by approximately 2 meters and the footpath was placed outside of the cable plane. In addition, the footpath railing was converted into a lightweight steel railing with maximum porosity, compared to the heavy concrete railing with minimal porosity that was proposed in the base concept. Second, the modified diamond shape of the towers allows the cables anchored along both the left and right side of the superstructure to meet at a common point in the tower head which significantly increases the effective torsional stiffness of the superstructure system. By increasing torsional stiffness, a greater separation between the first vertical natural frequency and the first torsional frequency is achieved and the potential for flutter instability is thereby minimized.

Even with the design features mentioned above, the bridge still has the potential to be aerodynamically unstable. To further investigate this issue, a comprehensive wind tunnel evaluation was performed using a sectional model approach (Figure 8). Consideration was given to vortex shedding accelerations at moderate wind speeds, dynamic buffeting demands at the design wind speed (36 meters/second), and flutter instability at the 10,000-year wind speed (54 meters/second). Testing confirmed that the structural configuration and aerodynamic shaping of the bridge resulted in a structure that was stable under all considered wind speeds, thus eliminating the need for supplemental wind fairings. Furthermore, additional sectional model tests with a 1:32 scale model at low to moderate wind speeds using vertical and torsional damping ratios of 0.006 concluded that no vertical or torsional vortex induced motions were observed [Raggett 2011].

Figure 8 - Sectional Model in Wind Tunnel

LIVE LOADING – The live load model for bridges in India has been established by the Indian Roads Congress and for major road bridges include an arrangement of wheeled and tracked vehicles which include a 70-tonne tank and a 100-tonne seven axle truck. This loading scheme is considerably greater than actual vehicle loads and has shown to be one of the heaviest in the world [Ponnuswamy 2008]. Consequently, live load demands are large and with a lightweight main span, an initial analysis of the bridge without the intermediate piers revealed that the side spans were prone to large moment peaks due to live loading. In order to reduce these peaks to levels more congruent with the remainder of the bridge, intermediate piers were utilized to stiffen the entire cable stayed system, thereby reducing deflections and moments in the sidespans. The actual magnitude of reduction that the intermediate piers made is significant as indicated in Figure 9, where the solid red line represents the case with the intermediate piers. It should be noted that the intermediate piers were also effective in reducing bending demands in the pylons (Figure 10).

Figure 9 - Superstructure Live Load Moment Envelope With and Without Intermediate Piers

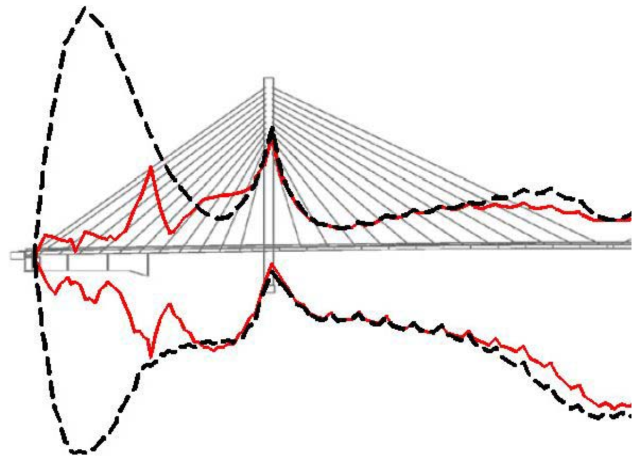
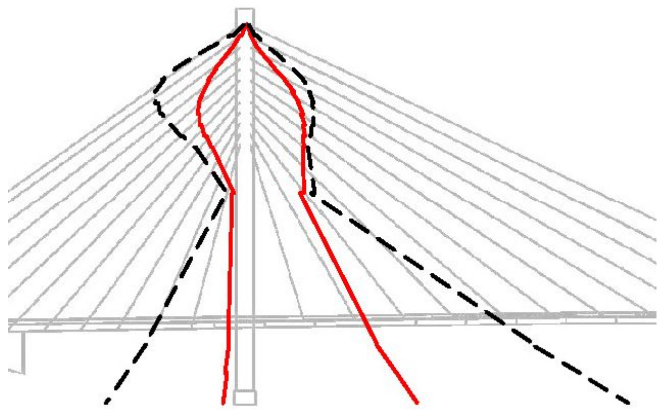


Figure 10 - Tower Live Load Moment Envelope With and Without Intermediate Piers



CODES AND REGULATIONS – To date the most challenging aspect of the Basohli Bridge development and design process has been dealing with the Indian Roads Congress (IRC) design codes. Cable-stayed bridges are inherently complex structures and as such there is currently no design code available which explicitly deals with all facets of their design; however, certain portions of the IRC code were found to be especially inadequate and required that we fall back on other international design codes and basic principles of structural mechanics.

To compound matters, the IRC design codes were currently in the midst of being transformed from allowable stress design (ASD) to limit states design. At the time the design of the Basohli Bridge started, the IRC Concrete section was ASD; however, the IRC Steel and Composite sections were limit state. It was therefore necessary to use both ASD (*for concrete elements – pylons, sidespan and deck slab*) and limit state (*for steel elements and composite components*) design philosophies for a single structure. This created numerous complications, inefficiencies and potential for errors. This multiple approach to design created confusion for elements such as the mainspan concrete deck which was partly designed according to the limit state code since it is part of the composite girder system; however, it was also designed according to the ASD code as a concrete member for local bending demands. To increase the drama, part way through the design phase the Indian Road Congress issued the limit state version of the concrete design code. Even though a significant amount of the design was completed prior to the new code being issued, the design was voluntarily updated to the newest code so the entire structure would be in conformance with one design philosophy.

CONCLUSION

Numerous constraints and design issues were overcome in the design process for which the outcome is discussed in this paper. As a result, construction of the foundations and pylons is proceeding as planned with construction of the entire bridge scheduled for completion in early 2014. When complete, the Basohli Bridge will be the first cable-stayed bridge built in India under a design-build contract.

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