Building Blocks

updates and information on structural materials

Knickerbocker Bridge in Boothbay, Maine.

Hybrid-Composite Beam Technology

A Cost-Effective, Safe and Sustainable Bridge Construction Method

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Remote country roads were once the only location for small single-span composite bridges. With the limitations in span lengths and the load carrying capacities of early fiber reinforced polymer (FRP) bridges, this was the logical and safe place to start. Eventually composite bridge technology would advance and technology would allow the use of composite materials in larger bridge structures. Today composite materials are used safely and cost-effectively on a variety of bridges throughout the United States.

This new technology, Hybrid-Composite Beam (HCB), is an emerging structural technology that utilizes concrete, steel and fiber reinforced polymer in an embodiment that exploits the inherent advantages of each of these materials. The HCB combines the strength and stiffness of conventional concrete and steel with the lightweight and corrosion-resistant advantages of advanced composite materials.

The concept of the HCB was originally conceived in 1996. Over the course of the next ten years, substantial progress was made under the High Speed Rail-Ideas Deserving Exploratory Analysis program (HSR-IDEA) of the Transportation Research Board (TRB). The concept started out of academic curiosity, with just a few hand calculations attempting to predict the behavior of this unusual structural member.

Goals of the HCB

Throughout the development of the HCB, the goal was to develop a revolutionary bridge system that exploits the inherent benefits of FRP materials, but at the same time is compatible with the types of conventional structures in terms of design as well as construction. The result is a new alternative for rebuilding the world's infrastructure with state-of-the-art structures having the following characteristics:

- Lightweight – 1⁄10 the weight of concrete and 1⁄3 the weight of steel.
- Safer – Internal redundancy and serviceability design result in capacities that greatly exceed code requirements. Reduced mass and resilient, energy absorbing materials offer excellent resistance and elastic response to seismic forces.
- Reduced Carbon Footprint – Beams use 80% less cement, one of the largest contributors to the carbon footprint. They also require 75 to 80% fewer trucks for shipping, and smaller cranes for erection and reduced emissions.
- Congestion Relief – Lighter, modular bridge system allows for Accelerated Bridge Construction and reduced traffic congestion during construction.
- Sustainability – No painting, rusting, cracking, spalling or alkali-silica reactions (ASR) results in a sustainable technology that provides for projected 100+ Year Service Life.

HCB Fabrication and Construction

To fabricate the Hybrid Composite Beam system, the FRP box beam is laid-up in a mold with the tension reinforcement in place. Lightweight foam is used to hold the shape of the arched conduit during fabrication. The

FRP box beam is then infused with resin and removed from the mold.

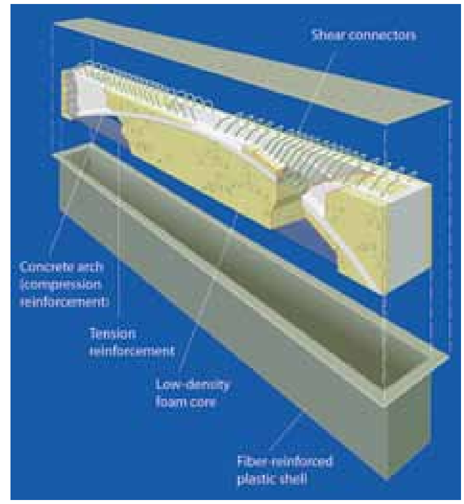
This lightweight beam is shipped to the bridge site, where it can be installed without the use of heavy cranes or lifting equipment. Accidents and injuries related to cranes have become more frequent in recent years. Because the HCB is a substantially lighter weight structural member (1⁄10 that of prestressed concrete), significantly smaller cranes can be used for installation. In most cases, the beams can be safely set with 30-50 ton cranes instead of 150-300 ton cranes. This provides a much safer working environment.

Once in place, Portland cement concrete is pumped into the arched conduit and is allowed to cure while the concrete fluid load is fully supported by the FRP box beam. Once cured, the concrete arch acts as the compression portion of the beam that is equilibrated by the steel tension reinforcement. Although typically filled in-place, the concrete arches and deck slabs of the HCB may also be precast prior to erection, resulting in an entirely prefabricated bridge element. Although this construction methodology reduces the lightweight advantage of the technology, it also demonstrates the flexibility to accommodate accelerated bridge construction. Using these construction techniques, a bridge superstructure could literally be installed and put in service within the same day, resulting in substantial congestion relief.

Design Methodology

Although the HCB contains materials that are generally new to most practicing structural engineers, with a basic understanding of the mechanics of Bernoulli-Euler beam theory and a working knowledge of standard bridge design codes, it is not difficult to assess the load carrying capacity of the HCB. In fact most design codes, including the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering and Maintenance-of-Way Association (AREMA), are compartmentalized and allow the engineer a fair amount of flexibility in assessing how forces are resisted by a structure. Further, the applied loads as well as the load and resistance factors can easily be rationalized for assessing the response and structural capacity of the HCB.

The bending capacity of an HCB is calculated using strain compatibility and force equilibrium in the same manner as a reinforced concrete beam. The major difference is the additional contributions from the FRP box. Alternatively, one can generally get an approximate answer within 5 to 10% of the exact answer simply by taking the compression force in the concrete, i.e. the slab and arch, and equilibrating it to a tension force in the steel tension reinforcing in the bottom flange. In other words, the nominal moment capacity of the section is as shown in *Equation 1 (page 32)*. Validation of the approximate solution can be found by using the rigorous strain compatibility and force equilibrium



Fragmentary perspective of the hybrid-composite beam.

calculations, and setting the areas of the various FRP components to zero.

$\Phi M_n = C(d - a/2)$ (*Equation 1*)

Where:

C = $f_c'ab$ (the compression force in Whitney's equivalent stress block)

d = the distance from the centerline of the steel reinforcement to the top of the beam

a = the depth of concrete in compression

In quantifying the shear resistance of the HCB, the first component is to establish the thrust in the arch at a given section and discretize this force into horizontal and vertical components. The vertical component can then be deducted from the gross shear on the section, as this is being resisted by the arch. The remaining shear is then resisted primarily by the FRP webs, but also by the thin concrete web above the arch. This results in a hybrid resistance to the shear forces in the beam. There are also some other interesting facets of the shear behavior that very much emulate a reinforced or prestressed concrete beam. For example, when the loads are applied to the structure to produce maximum shear effects, e.g. adjacent to a support, the majority of the shear is resisted strictly through the arching action similar to the strut and tie behavior.

There are inherent benefits to public safety resulting from the structural behavior of the HCB. Since design is usually governed by satisfying live load deflections, the HCB consistently exemplifies significant reserve capacity for strength. In fact there is enough redundancy in the HCB that, in many cases where the bridge deck was completely deteriorated, the HCB would still have sufficient capacity to carry all of the factored design loads applied to the bridge. Laboratory tests have consistently confirmed bending and shear strength capacities well beyond the code specified factored demand.

Out of the Laboratory

Development of the design methodology, manufacturing process and structural validation was a long and arduous process that encompassed over a decade of sheer perseverance. In 2007, the first real demonstration of a HCB Bridge took place on the test track at the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO. Not only was this the first application of an HCB Bridge, but it was also the first installation of an FRP railroad bridge anywhere in the world.

The first installation of an HCB highway bridge began with the construction of the High Road Bridge in Illinois. This bridge comprises a 57-foot single span bridge that carries two lanes of traffic over Long Run Creek. The superstructure is comprised of six 42-inch deep by 20-inch wide HCBs supporting a conventional 8-inch thick reinforced concrete deck with an out-to-out dimension of 43 feet and a curb-to-curb width of 40 feet. The HCBs are spaced at 7-feet 4-inch centers.

The bridge's six beams, each 58 feet long, weighed less than 4,000 pounds, so all six beams could be shipped on one truck. Had these been precast concrete beams, it would have required six trucks instead of one. The contractor was also able to erect the beams with a 30 ton utility crane instead of a 150 to 200 ton crane.

Another milestone in HCB technology took place in the summer of 2011 with the completion of the Knickerbocker Bridge in Boothbay, Maine, which constitutes the longest composite bridge constructed to date anywhere in the world. In order to comply with the hydraulic criteria for the new Knickerbocker Bridge, the HCBs were designed to match the recommended 33-inch deep box beams in order to maintain the required vertical underclearance. Also, similar to the proposed precast box-beam bridge, the HCB framing system was limited to two 60-foot end spans and six 70-foot interior spans resulting in an 8-span bridge with a total length of 540 feet. The beams were also made continuous for live load with negative moment reinforcing steel cast over the piers in the 7-inch concrete topping slab.

Another advantage of the lightweight nature of the beams was that it allowed the contractor to ship the beams across the existing timber trestle that was posted with load restrictions. In general, the HCBs were erected at a rate of approximatey 16 beams per day. After setting the first four spans of the bridge, the contractor placed the concrete for the arches in the HCB units. By simply placing a hopper with a steel tube into the tops of the beams, it was possible to fill each beam in approximately ten minutes.

Once the beams were filled, the contractor began placing reinforcing for the deck pour. Scupper details, screed rails and reinforcing details were no different than those for a comparable precast concrete bridge. The first half of the deck was cast in October 2010. After working through the winter to complete the remaining piers, the contractor completed installation of the second half of the HCB superstructure in April 2011. The bridge was officially opened to traffic on June 11, 2011. When all was said and done, the cost of the HCBs for the Knickerbocker Bridge was no more than it would have been for a conventional bridge, making this one of the first composite bridges to be economically viable on a first cost basis.

HCB in the Show Me State

In June 2009, the Missouri Department of Transportation (MoDOT) let a single Design-Build contract to replace 554 small bridges located in rural areas throughout the State of Missouri. When completed in 2012, the Safe & Sound Bridge Improvement Program will have replaced the 554 deteriorating bridges that are no longer cost effective to maintain, as well as 248 bridge rehabilitation projects.

KTU Constructors, a joint venture consisting of Kiewit Western Co., United Contractors, Inc. and Traylor Bros., Inc., proposed using standard precast concrete box beam and voided slab construction on a majority of the bridges in the program. However, as part of a Highways for Life Award from the Federal Highway Administration (FHWA), MoDOT plans to use HCBs in place of the precast concrete box beams on three of the replacement bridges. This is a first time use of the HCB system in Missouri.

The first of the three bridges is Bridge B0439 that carries MO 76 over Beaver Creek, just outside of Jackson Mill. This bridge comprises a three-span structure with typical spans of 60 feet and an overall length of 180 feet, and was opened to traffic in November 2011. The remaining two bridges will be constructed in the first half of 2012, including Bridge B0410 carrying MO 97 over Sons Creek. This bridge, with a single span of 106 feet founded on integral abutments, will establish yet another milestone in span length for HCBs. The cross-section itself is comprised of three, 60-inch deep, double-webbed HCB boxes that only weigh 9 tons each.

The Future

The significance of the success of these bridges will hopefully pave the way for additional advancements in composite bridge construction. Currently additional bridge installations are slated in Maryland, Virginia, Utah and West Virginia, to name a few. With economies of scale and further advances in fabrication automation, it is now possible, with the HCB, to make sustainable structures using advanced composites a mainstream component for reconstruction of the world's deteriorating infrastructure.▪