The Hillman Composite Beam

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ABSTRACT

Commercialization of the "Hillman-Composite Beam" (HCB) began with the first installation in 2008. Since that time, over 40 spans have been installed in North America with planned installations in Australia for 2017. The HCB comprises three main sub-components that are a shell, compression reinforcement and tension reinforcement. The shell comprises a fibre reinforced polymer (FRP) box beam. The compression reinforcement consists of self-consolidating concrete in a profiled conduit within the shell. The tension reinforcement consists of steel fibers infused in the bottom flange. The unique combination of materials in an HCB basically comprise a "Tied-Arch in a Fibreglass Box". The HCB combines the strength and stiffness of conventional concrete and steel with the lightweight and corrosion-resistent advantages of advanced composite materials. What results are sustainable structures that are lighter, stronger, more corrosion resistent and more resilient than bridges of conventional materials. Not only has the HCB made possible the first composite freight rail bridge in the world, the longest composite bridge in the world at 165 m and the longest girder span for conventional highway loadings at 32 m, but it has demonstrated that hybrid FRP structures can be competitive with conventional bridge materials on a first cost basis.

INTRODUCING HCB

Before there were smart phones and wireless Internet, the greatest innovators in the world, were bridge engineers. Civil engineers and more specifically, bridge engineers, literally ushered in the "Iron Age" and later the "Steel Age" with innovative bridges. Further, every great paradigm shift in the bridge world originated from a patented idea or "Intellectual Property", generally marketed as a proprietary product. "The bucolic covered bridge; the ethereal appearance of prefabricated metal trusses thrown across numerous streams; traditional arch and girder forms appearing in the garb of a new material, reinforced concrete – these altogether elicited more than eight hundred patents during the first century of the U.S. Patent Office" (Kemp, 2005). Even newer advances including suspension bridge technology, movable bridges, and prestressing and post-tensioning of reinforced concrete, were all the result of patented intellectual properties.

Our heritage as engineer-inventors is still alive and a new class of structures and bridge products continues to emerge, many using advanced high-performance materials. Although not as ubiquitous as the "Catalogue Bridges" that shaped the industry and the American landscape for nearly a century after the Civil War, these new technologies offer the same opportunities for a paradigm shift that will positively impact the quality of the built environment.

It was in this same spirit that in 1996, John Hillman invented what would become the patented, Hillman Composite Beam (HCB®) out of an insatiable curiosity to see what would happen if concrete and steel were combined with fiber-reinforced polymers (FRP). Developing the concept was the simplest part of the process, and then the hard work began. Over the course of the next eleven years, with funding from the Transportation Research Board (TRB), Ideas Deserving Exploratory Analysis (IDEA) Program, John Hillman and Mike Zicko set about to develop the design limit states, manufacturing process and construction methodologies to make the HCB a viable alternative to conventional bridge construction.

At the time of the HCB's inception, the highway bridge markets had all but exhausted their interest in finding a practical application of FRP composites for bridge structures. Conversely, the Class 1 Railroads had never even considered the possibility. Serendipitously, when applying for research dollars it was the railroad industry and not the highway market that expressed an interest in the HCB's success. Upon completion of a successful laboratory test, representatives of the highway industry agreed to co-fund the further development of the HCB. Regardless, by this time the die was cast and the HCB's destiny was to see its first deployment as a Class 1 Railroad bridge. Ultimately, this was fortuitous for the HCB's long-term acceptance, as it is hard to argue these beams would have insufficient capacity for a pedestrian bridge or highway structure after validation under Cooper E-80 railroad loading.

Several beams were tested at the University of Delaware, Center for Composite Materials (CCM) as part of this research, including fatigue testing of one-million cycles of Cooper E-80 live load. The successful conclusion of this research was realized in the deployment of the world's first composite railroad bridge that was tested at the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO on November 7, 2007.

The original HCB Bridge comprised a simply supported, 9.32m span designed for Cooper E-80 locomotive loads as specified in the AREMA design codes. This bridge along with a 12m. HCB span were collectively subjected to over 500 Million Gross Tons (MGT) of heavy axle Class 1 railroad loadings over the course of about four years. This equates to roughly three million cycles of fatigue live load stresses on the bridge, with no evident change in the performance. This essentially validated the performance of the HCB for the Class 1 railroad community in North America, and this technology has already been deployed on a revenue service line for CP Rail in Fernie, BC, with additional revenue service railroad bridges soon to be deployed.

Figure 1. First HCB Bridge at Pueblo, CO

Even before the railroad tests were concluded, several HCB highway bridges were deployed in service. The earliest bridges were installed in Illinois, New Jersey and Maine. Like the railroad bridges, a representative beam of each of these structures was subjected to fatigue and loaded to failure prior to construction of the respective bridge. Typical Inventory Ratings have been found to be on the order of 2.7 and Operating Ratings as high as 3.5. Subsequently, the engineering community could feel comfortable that the HCB as designed could safely support the code specified factored demand with considerable additional capacity.

GENERAL BEHAVIOR OF THE HCB

The HCB includes components that are unfamiliar to most bridge engineers. Further, there is limited information regarding the design of the FRP composites offered in the typical Civil Engineering curriculum or in bridge design codes. Regardless, many of the fundamental principles of design for concrete and steel can be used and extrapolated using some engineering judgment to arrive at a safe and predictable design. Further, over the past two decades, design information has been compiled in American Concrete Institute, ACI 440 to address the integration of FRP composites into concrete structures in several different embodiments. Some of these provisions can be used to address the design of an HCB.

For the most part, an HCB behaves exactly like a reinforced concrete beam in the bending limit state. The capacity can easily be predicted using strain compatibility and force equilibrium simply by considering the arch concrete and the supported reinforced concrete deck to determine the compression resistance of the force couple. The tension side of the resisting couples is primarily provided by the steel tension tie, which typically comprises 270 ksi, low-relaxation, galvanized strand. Additional bending capacity is also provided by the FRP shell and with a little bookkeeping, the exact bending limit state can accurately be predicted.

The ultimate shear capacity is a little more complicated, but again, is like what we see in beams fabricated of other materials. The shear behavior comprises a unique sharing of capacity between the concrete arch and the webs of the FRP shell. Towards the center for the beam, where the arch is very flat, the FRP webs primarily resist the shear. The quad-knit glass fabrics used in the shell have four separate plies oriented along the longitudinal axis, the transverse axis and plus/minus 45 degrees. These 45-degree plies allow the laminate to develop tension field action to fully mobilize the tension capacity of the laminates along the orientation of the principal stresses. In laboratory tests, it is not unusual to see the laminate buckle along the compression diagonal as the applied force exceeds the factored design live load. The laminate then debonds from the low-density foam core, exhibiting the tension fields typically evident in an efficiently designed steel plate girder, as evident in Figure 2.

Towards the beams ends, the curvature of the arch comprising the concrete compression reinforcement provides a “Resal’s Effect,” whereby the shear gets transferred in a pure strut and tie model carried to the bearings. Steel reinforcing bars (shear connectors) are also inclined along a 45-degree angle inside of the HCB to connect the arch to the supported deck. This not only allows the concrete deck to act compositely with the beam, but also provides for a very effective shear reinforcing of the concrete fin connecting the arch to the deck. This combined resistance provided by the FRP and concrete arch results in shear capacities that typically exceed the design service loads required by codes by three times.

Analytical models, corroborated by experimental results have demonstrated that the HCB’s strength capacity exceeds code requirements by more than a safe margin. In fact, serviceability limit states usually control the design of the HCB. More specifically, the live-load deflection requirements determine the amount of steel necessary for code compliance. This is in part a characteristic of the FRP laminates’ properties. Despite their tremendous strength, they have a high strain to failure rate. The composite laminate typically has a modulus of elasticity on the order of one tenth that of the steel. Subsequently, adding steel strands typically controls deflections. Since very high-strength steel is used for the tension tie, when considering the bending limit state, the HCB is typically qualified as over-reinforced. Regardless, the high factors of safety evident from experimental testing mitigate concerns about a brittle failure under the code design requirements.


Figure 2. Tension field action in HCB (photo courtesy of Virginia Tech).

Whereas the FRP materials need additional assistance from concrete and steel for the live load deflection requirements, these same characteristics, i.e. high-strength with low-modulus, provide superior resiliency when it comes to impact loads. They also offer tremendous synergy with current repair techniques using advanced composite materials.

FABRICATION AND CONSTRUCTION

The HCB is fabricated using a closed mould, vacuum-assisted resin transfer method (VARTM) to manufacture the composite shells. In this process, all the preforms, i.e. glass, foam and steel are placed in a mould. The mould is completely evacuated of air at which point the resin is pulled into the mould, wetting out all the constituent components into a monolithic shell. By filtering out any hazardous materials through the vacuum system, the VARTM process becomes is an environmentally friendly, zero VOC emission manufacturing process.

One of the biggest advantages of HCB is the extremely lightweight for shipping an erection. Twenty-two meter beams can weigh less than 3 tonnes. As a result, six to eight HCB's can be transported on a single truck instead of using one truck for each beam, which is common for precast concrete beams. Further, the contractor is usually able to erect the beams using a 30-tonne utility crane instead of mobilizing a 200-tonne crane. As contractors typically already have a small utility crane on sight, this results in a significant cost savings for installation. Examples of these benefits will be demonstrated in the following pilot projects.

High Road Bridge – Lockport Township, Illinois

The first permanent highway bridge to utilize the HCB is the High Road Bridge. The framing plan for the High Road Bridge emulates a very conventional bridge system. The bridge itself is a 17.4m single span bridge that carries two lanes of traffic over Long Run Creek in Lockport Township, Illinois. The superstructure is comprised of six 1067mm deep by 508mm wide HCB's supporting a conventional 200mm reinforced concrete deck with an out-to-out dimension of 13.15m and a curb-to-curb width of 12.2m. The HCB's are spaced at 2.24m centers. The shipping and erection advantages of the HCB can be seen in Figures 3 and 4.

It should be noted that the framing configuration was intentionally designed to be interchangeable with precast beams in that compatibility with conventional bridge design and construction can help expedite the acceptance of a new technology in the bridge industry. This particular deployment exploits the lightweight advantages of the HCB in that the arch concrete and deck are both cast-in-place.

Figure 3. Six HCB's on Single Truck


Figure 4. Erecting HCB with 30 tonne Crane

The High Road Bridge was originally scheduled to be open at the end of November, 2008. Despite a month of delays from weather and utility relocations as well as the prototype testing and learning curve associated with the first deployment of this new technology, the bridge was opened three months ahead of schedule on August 25, 2008. As a result of careful monitoring of every aspect of construction, this project was completed ahead of schedule as well as under budget.

When all was said and done, the cost of the HCB's for the High Road Bridge was no more than it would have been for a conventional bridge. The only premium was related to the prototype testing and research aspects of the project that were covered at 100% by the discretionary IBRD funds. Despite learning curves associated with the implementation of new technology, there was no impact to the project schedule because of the use of the HCB. With improvements to the overall system resulting from lessons learned on the High Road Bridge Project, further refinements to materials and manufacturing processes make this technology competitive with concrete and steel on a first cost basis.

Knickerbocker Bridge – Boothbay, Maine

The next level of development of HCB Bridge technology was exhibited in the Knickerbocker Bridge, completed in Boothbay, Maine in 2010. This structure is comprised of an eight-span continuous HCB superstructure with 18.3m end spans and 21.3m interior spans. The framing system comprises eight 838mm deep HCB's at 1.24m centers supporting a 178mm reinforced concrete deck. Additional negative moment reinforcing steel is provided in the deck, over the piers to make the superstructure continuous for live load. This bridge set a new benchmark for the deployment of composite bridge technology with an overall length of 164.6m.

This configuration of an HCB bridge is designed to be a direct substitution for precast box beam bridges. Again, the actual beam unit is only 610mm wide at the base, but still has a 1244mm top flange. Once erected, the tips of the flange overhangs are side by side, eliminating the need for any deck forming. Again, these types of girders can be installed empty, with concrete arches or with the deck already cast. Even with the top slab precast in a yard, these units would still be lighter than precast box beams and would not require an additional overlay. The Knickerbocker Bridge was open to traffic in spring of 2011 and is still functioning with no problems or maintenance concerns despite the aggressive environment on the coast of Maine.

HCB Conquers the Class 1 Railroads.

Satisfied with the performance of the prototype HCB span, the railroad bridge engineers in North America decided it was time to proceed with a production version of the HCB, taking advantage of improvements in the production process as well as lessons learned from the prototype test. The BNSF Railway procured a 42-foot span with the intent that it be proof-tested by TTCI for a similar period as the prototype HCB. After proof testing it was to be installed in revenue service. The span length was chosen, as it was the longest span available in the concrete test bridge.

This second-generation HCB span was installed and proof-tested in conditions similar to those for the 9.32m prototype span as described earlier. This span has also accumulated 244 million gross tons of traffic representing about 1.5 million load cycles. See Figure 5. There has never been any evidence of the change in performance due to fatigue cycling, either in the laboratory or insitu testing at TTCI. Further, it is important to note that as the amount of steel is generally driven by deflection requirements, and high strength steel is being used, the strain levels in the tension reinforcement under service loads are typically below the constant amplitude fatigue threshold for the strand. Subsequently, no fatigue failures were anticipated.

Figure 5. Test train crossing 42-foot HCB span at TTCI Pueblo, CO, test facility

Strain and deflection measurements indicated the 12.8m span performed in a more uniform manner from cell to cell as compared to the original prototype span. This reflects well on the improvements made in the production process. Deflections were also lower as a percentage of the recommended industry maximums as compared to the prototype span. The 12.8m HCB span was similar in weight to a 9.32m prestressed concrete span, enabling longer spans to be handled and erected, particularly using on-track cranes.

The 12.8m HCB span was removed from proof testing after a similar amount of traffic as the prototype HCB span and was placed on a BNSF revenue service line in Colorado in 2015. Strain gages and wiring were left in place on the span to facilitate measurements under revenue-service traffic.

FIRST HCB BRIDGE IN AUSTRALIA

Ten years after the proof of concept of the first bridge in Pueblo, Colorado, the HCB has found its way across the Pacific Ocean to Australia. In September of 2017, Waeger Industries in collaboration with A.C. Whalan Composites initiated the fabrication of the first HCB bridge outside of North America. Selected as the first candidate is Bridge 2 on West Street, Greta. This bridge comprises a single span of 14.825m with a deck width of 12.4m carrying two lanes of traffic and a shared path for bicycles and pedestrians.

The bridge is also oriented on a 40-degree skew to accommodate the flow of the creek with respect to the roadway. Although this is a relatively severe skew, a 45-skew bridge of similar span length was erected in Tides Mill, Virginia in 2013. Prior to installation of the 45-degree skew, extensive testing was conducted at Virginia Tech to assess the effects of skew on an HCB Bridge, including a full-size mock-up of a three-beam assembly. In general, it was found that the HCB is well suited to skewed bridges in that the inherent torsional stiffness of the FRP box mitigates the need for any intermediate diaphragms as would be required in a steel bridge. Further, the flexibility of the HCB units, constructed with a conventional 200mm concrete deck adequately distribute the skewed live load effects without the reflective cracking often seen with an adjacent concrete box beam bridge.

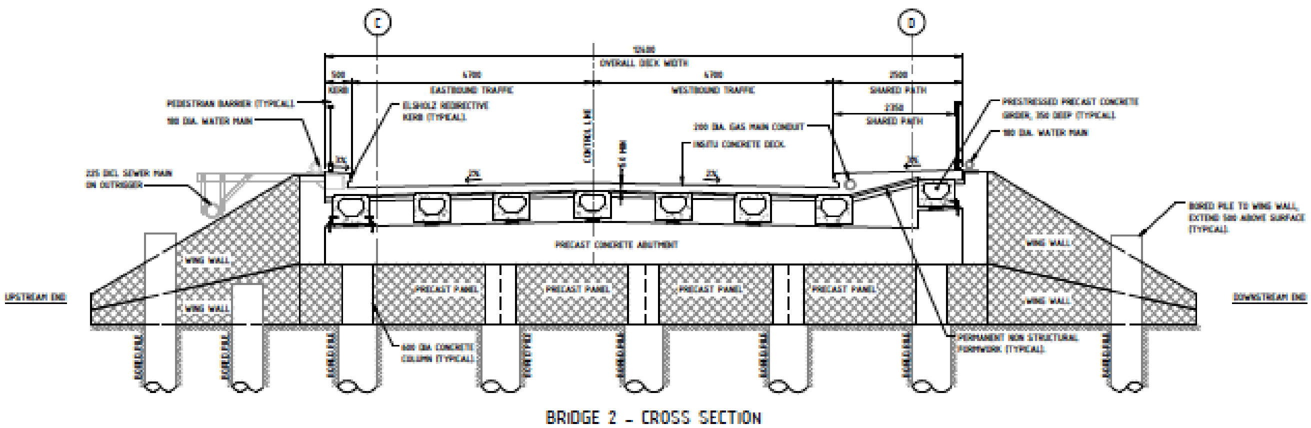

Figure 6. Cross-Section of Bridge 2 – West Street, Greta

There were no modifications to the embodiment of the HCB to facilitate deployment in Australia other than just ensuring that the beams were designed in accordance with the Australian Bridge Design Codes using the AS5100 loading. In this regard, HCB worked closely with the engineers at Northrup Consulting Engineers Pty Ltd to make sure that components of the HCB were compliant to the limit states in the Design Criteria for Bridge and Other Structures, Transport and Main Roads, March 2017. Despite different axle configurations and load factors, the designs between the US version of an HCB and an Australian version of an HCB are essentially the same except for slightly higher shear loads in the Australian codes.

Figure 7. Typical HCB unit for Bridge 2 – West Street, Greta, being loaded on truck with forklift.

The HCB units for the West Street Bridge 2 have now been fabricated and it is expected that this bridge will be open to traffic in Late 2017 or early 2018. Figure 7 shows a photograph of the first Down Under HCB being loaded on the truck for delivery. Again, all six beams for the truck can be loaded onto a single truck, making shipping and installation with small erection equipment a viable alternative for expedited bridge construction.

CONCLUSIONS

It is rapidly becoming common knowledge that the world's infrastructure is in an advance state of decay and obsolescence. The introduction of the HCB offers in an innovative, cost effective and sustainable advancement in engineering with far reaching socioeconomic impacts. The HCB provides a revolutionary bridge technology that demonstrates a commitment by the civil engineering community to not only rectify the state of our decaying infrastructure, but also to provide a solution to this problem that will reduce the burden of decaying infrastructure for future generations.

West Street Bridge 2 in Australia demonstrates that HCB technology can be deployed anywhere in the world. Although the applicable design codes have to be followed, the materials, manufacturing technology and compatibility with conventional bridge components and construction techniques make HCB a valid substitute for concrete and steel beams in bridges anywhere in the world.

In addition to railroad and highway bridge structures, the HCB provides an attractive alternative to other types of structures as well, including marine structures like docks, piers and berths. The technology also lends itself well to green roof technology. There are many hurdles to introducing a new technology to a conservative industry like such as exists in the bridge world, not the least of which is our own reluctance as practicing engineers to embrace change. Regardless, opportunities still exist to advance our profession, albeit slowly and methodically. The HCB challenges the engineer to embrace change.

REFERENCES

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AUTHOR BIOGRAPHY

John R. Hillman, PE, SE is President & CEO of HCB, Inc. He has been involved in design and construction of unique bridges for over 31 years. His HCB invention has brought worldwide recognition including; the Construction Innovation Forum's 2010 NOVA Award and the 2013 Charles Pankow Award from ASCE. In 2010 Mr. Hillman was honored with the 2010 Engineering News Record – Award of Excellence and in 2013 he was recognized by the Obama White House as a "Transportation Champion of Change."