CANADA’S FIRST HYBRID-COMPOSITE BEAM BRIDGE

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Abstract: Long before Accelerated Bridge Construction (ABC) became ubiquitous in highway bridges, it was standard practice for the railroad industry. Rapid installation and long service lives are not just desirable qualities, they are essential. The hybrid-composite beam (HCB) provides a lightweight, safety-redundant and sustainable option for the next generation of railroad bridges with these essential qualities. It is equally well-suited for ABC of highway bridges. The HCB is comprised of three main sub-components that are a shell, compression reinforcement and tension reinforcement. Design, fabrication, endurance testing, constructibility, inspectabilty and maintainabilty will be addressed from several points of view resulting from a unique collaboration between Transportation Technology Center, Inc. (TTCI), Canadian Pacific Railway (CP) and HCB, Inc. Although 14 HCB bridges comprising 29 spans have now been constructed, the evolution of this technology started with the first proof of concept on the HTL at TTCI in November 2007. This paper chronicles the seven-year journey from proof of concept that culminated in the first HCB bridge in Canada and the first revenue-service HCB railroad bridge anywhere in the world. It will also demonstrate how an HCB unit damaged during transportation was efficiently repaired to restore its original integrity to safely carry heavy axle load traffic on a CP mainline through the Canadian Rockies. In addition, the paper presents what happens when the internal components of an HCB bridge are exposed or damaged. Examples will be provided showing current research related to impact testing and residual capacity of a damaged HCB.

1 THE ORIGIN OF THE HYBRID-COMPOSITE BEAM

1.1 Genesis of the Hybrid-Composite Beam

For several decades now, engineers have experimented with various ways of integrating fibre-reinforced polymer (FRP) composites into bridge structures. These materials offer numerous advantages in terms of their lightweight characteristics, corrosion-resistant properties, strength and resilience. Despite these advantages, FRP composites have struggled to find the optimum application in the infrastructure market. In 1996, the hybrid-composite beam (HCB) was conceived as a potentially cost-effective way to exploit the unique characteristics of FRP materials by combining them with the conventional building materials of steel and concrete. Utilizing a slender, shallow concrete arch, with a tension tie of high-strength steel all encapsulated in an FRP shell, a structural member that is lighter, stronger and more corrosion-resistant emerges as an economical alternative to conventional structures.

1.2 Research and Development of the HCB

The HCB also represents a cross pollination of the heavy civil bridge construction world with the composite manufacturing world. Intuitively, the concept of the HCB is quite simple, but the tools to design, fabricate and construct a bridge of this embodiment exceeded the current practice at the time of conception. For the most part, the standard design codes such as AASHTO and AREMA could be adopted to address the design limit states. Still, consideration and engineering judgment were necessary to extrapolate the provisions of the current code to assess the capacity side of the design limit states. In particular, it was necessary to address the contribution from the FRP components working in concert with concrete and steel to provide the ultimate bending and shear capacity.

Likewise, the fabrication of the HCB presented some interesting challenges. The original idea for the HCB was inspired by the flexibility afforded from Vacuum Assisted Resin Transfer Moulding or VARTM. This is a composite manufacturing process where the laminates are manufactured by using a vacuum pump to evacuate all of the air in the preforms, e.g., glass fabrics. Once all of the air has been evacuated from the part layup, the vacuum pulls the resin through the component parts until all of the glass is wet out and completely saturated with the liquid resin. Once the resin cures, the rigid part can be removed from the tooling. The whole process is very quick, inexpensive and environmentally friendly. A typical beam can be manufactured in one day with very little investment in the manufacturing equipment.

The VARTM process used for HCBs has become somewhat ubiquitous in composite manufacturing and is commonly used for the manufacturing of large wind blades, boat hulls and rail transit cars. Despite the evolution of this manufacturing process, the HCB provided interesting challenges in the need to incorporate the steel fibres for the tension tie and manufacture in a closed-mould process with a hollow cavity for later placement of the concrete for the compression reinforcement in the arch.

1.3 Evolution in the Laboratory

Development of technology for transportation infrastructures is a long, expensive and laborious task. In order to get the concept from drawing board to reality, it was first necessary to secure research dollars to go from the initial sketches to an actual prototype. This early stage funding was secured through the Ideas Deserving Exploratory Analysis (IDEA) program from the Transportation Research Board (TRB). The first phase of the project was funded through the High Speed Rail (HSR) division of IDEA. The second stage was co-funded by the National Cooperative Highway Research Program (NCHRP) in conjunction with HSR.

Over the course of the next eight years, the IDEA research was undertaken by the inventors in conjunction with the University of Delaware, Center for Composite Materials (CCM). This research included: developing the design limit states to predict the HCB's response and capacity, developing the manufacturing process to establish the commercial viability and conducting the initial proof of concept in the laboratory to ensure the HCB would have adequate capacity to support the code specified, factored demand for a Class 1 Railroad bridge.

1.4 Design Methodology and Capacity Validation

As noted, 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 couple of decades, design information has been compiled in ACI 440 to address the integration of FRP composites into concrete structures in several different embodiments. Some of these provisions can also 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 1860 MPa, 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 be predicted fairly accurately.

The ultimate shear capacity is a little more complicated, but again, not terribly different from what we see in beams fabricated of other materials. The shear behaviour 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 forces exceed 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 1.1. 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 three times the design service loads required by codes.

Figure 1.1. Tension field action in laboratory (Courtesy of Virginia Tech)

Analytical and experimental results have typically demonstrated that the HCB's strength capacity exceeds the code requirements by more than a safe margin. In fact serviceability limit states usually control the design of the HCB. More specifically, it is the live-load deflection requirements that 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. In reality, the composite laminate typically has a modulus of elasticity on the order of one tenth that of the steel fibers. 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.

2 HCB PROOF OF CONCEPT BY THE RAILROAD INDUSTRY

2.1 Out of the Frying Pan and into the Fire

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 loadings.

During the development stage, several small-scale beams and two full-size, 30-foot-long HCBs were tested in the laboratory to failure. One of the 30-foot beams was also subjected to 2,000,000 cycles of fatigue live load before being loaded to failure. The last stage of the HSR-IDEA investigation was to fabricate a complete HCB railroad bridge and deploy the system on the Heavy Tonnage Loop (HTL) at the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO. The bridge installed at TTCI was delivered as two units. Each unit comprised four each, 30-foot HCBs tied together with a 4-inch composite concrete deck and concrete ballast curbs. Each piece weighed approximately 44,000 lb. The entire bridge was installed in a matter of hours using a 50-ton rough-terrain crane.

2.2 Trust but Verify

On November 7, 2007, after 11 years of research and development, the first HCB bridge was proof-tested under real live Class 1 Railroad conditions at TTCI. See Figure 2.1. The initial tests were conducted over a two-day period, after which the HCB bridge was inspected. The HCB beam elements performed well, but the reinforced concrete deck had some cracking.

Figure 2.1: Test train crossing 30-foot prototype HCB span at TTCI Pueblo, CO, test facility

The original concrete deck was 4 inches thick with minimal wire-mesh reinforcement. This deck was removed and replaced with a -6-inch-thick deck with top and bottom reinforcement in both the longitudinal and transverse directions. The deck thickness and reinforcement was selected to match that of prestressed concrete box girders with a history of excellent performance in railroad service.

After installation of the new concrete deck, the prototype HCB span was re-installed in the test bridge. The span was tested in heavy haul railroad service for about two years. The test train was typically made up of four locomotives and about 110 cars, each loaded to 315,000 lb. gross rail load. Typically, the test train ran at 40 mph. The test train has well-maintained wheels that do not generate significant impact loads. The span accumulated 237 million gross tons of railroad traffic, representing about 1.5 million load cycles.

The ballast deck test span was installed in a 5-degree curve with 4 inches of superelevation. The deck of the span was level (had no superelevation). Ballast depth below ties on the low rail was about 8 inches. Four inches of additional ballast was placed beneath the ties on the high rail side of the track, for a total of 12 inches of ballast depth below the high rail.

TTCI engineers recorded deflection and strain measurements during the course of testing. No significant changes were noted over the course of testing. As expected, deflections for the HCB span are greater than for a typical prestressed concrete box girder railroad span of the same length, due to the much larger effective cross section in a typical prestressed box girder for railroad service. Details of the measurements are available in the references (Otter and Doe 2009, Otter and Tunna 2011, Mademann and Otter 2013).

Satisfied with the performance of the prototype HCB span, the railroad bridge engineers 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 30-foot prototype span as described above. This span has also accumulated 244 million gross tons of traffic representing about 1.5 million load cycles. See Figure 2.2. 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 a 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 2.2: Test train crossing 42-foot HCB span at TTCI Pueblo, CO, test facility

Strain and deflection measurements indicated the 42-foot 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 42-foot HCB span was similar in weight to a 30-foot prestressed concrete span, enabling longer spans to be handled and erected, particularly using on-track cranes.

The 42-foot HCB span was removed from proof testing after a similar amount of traffic as the prototype HCB span. It is scheduled for installation during 2015 on a BNSF line in Colorado. Strain gages and wiring were left in place on the span to facilitate measurements under revenue-service traffic.

3 FIRST-REVENUE SERVICE DEPLOYMENT OF HCB

3.1 A Class 1 Railroad Responds to the Challenge

Bridge 32.84 Cranbrook Subdivision crosses a mountain creek on the CP mainline west of Fernie, BC. The bridge consists of a 10-metre-long deck plate girder (DPG) span supported on two large concrete gravity abutments constructed in 1904 (Figure 3.1). Modern 130,000-kg (286,000-lb.) freight car shear stresses exceeded the DPG Normal Rating by 10%, but were only 60% of Maximum Rating. The bridge supports curved track on a high-density freight mainline. A 1992 assessment revealed these 110-year-old spans may be nearing the end of their theoretical fatigue life. The bridge was carefully inspected until replacement. The substructures of this bridge have performed well without any evidence of translation or rotation. Therefore, it was decided to replace the existing DPG span with a modern ballasted deck span on the existing foundations without substantially increasing the total load on the abutments. Ballasted deck construction would increase superstructure dead load. However, superstructure dead load is a relatively small proportion of the total load on the foundation and an investigation of bearing pressures revealed ample capacity to accommodate the increased dead load. Furthermore, ballasted deck construction readily accommodates track curvature, reduces dynamic effects of the live load and reduces deck maintenance requirements. The existing DPG span steelwork weighed 9000 kg (20,000 lb.) and the timber tie deck weighed 10,000 kg (22,000 lb.).

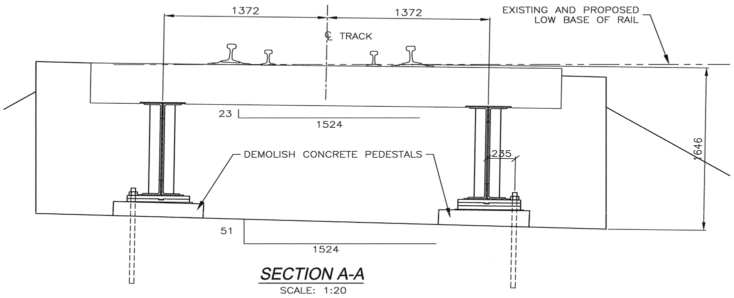

Figure 3.1: Cross section of existing steel deck plate girder span

Cost-effective accelerated bridge construction is a foundational practice at the railroad. Bridges must be erected with minimal interruption to rail traffic using low cost materials and methods. Therefore, the replacement span for Bridge 32.84 Cranbrook Subdivision must be of modular design with:

- ballasted construction,
- low-cost materials and fabrication,
- dimensions (weight and size) enabling lifts by rail mounted cranes (the bridge is accessible only by rail), and
- type and dimensions enabling rapid replacement.

The standardization of precast concrete railroad superstructures has enabled substantial reductions in short-span fabrication cost. Therefore, replacement of the existing DPG span with the railroad's standard precast prestressed concrete spans was first investigated (Figure 3.2). An appropriate standard span designed for Cooper's E80 loading had a concrete weight of 55,000 kg (120,000 lb.). The maximum weight of components being erected would be 27,500 kg (60,000 lb.).

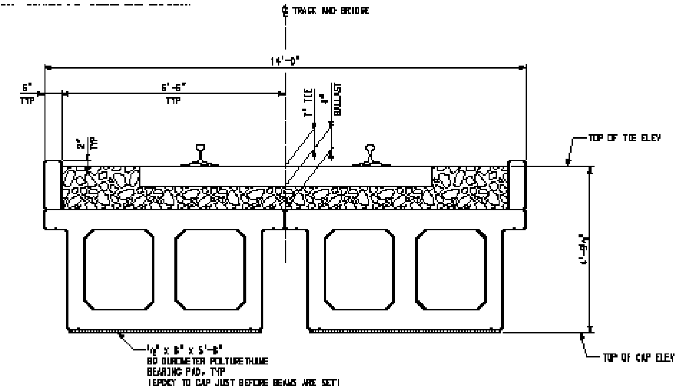

Figure 3.2: Cross section of proposed standard precast prestressed concrete span

A ballasted deck steel girder span was also investigated (Figure 3.3). The low available girder depth and Cooper's E80 design live load required a multiple girder span with a steel weight of 26,000 kg (57,000 lb.). The maximum weight of components being erected would be 13,700 kg (30,000 lb.). The lifting capacity is half of that required for the precast concrete span, but the estimated fabrication cost was 235% the cost of the precast prestressed concrete span.

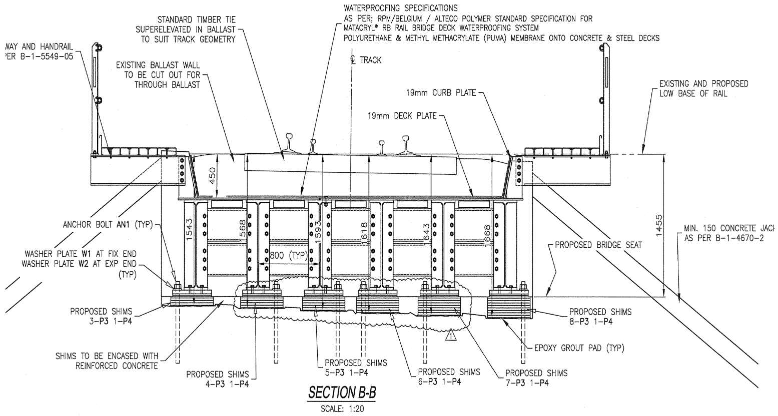

Figure 3.3: Proposed ballasted deck steel girder span

Concerns regarding the weight of a precast prestressed concrete span and fabrication cost of a ballasted deck steel girder span precipitated the investigation of alternative span types and materials. The railroad has been following the development of the HCB from initial involvement in a Class 1 railroad industry-funding consortium through laboratory and heavy-axle load field testing. Therefore, an HCB span was also investigated (Figure 3.4). The HCB design could readily accommodate the low available girder depth with a weight of 38,000 kg (84,000 lb.). The maximum weight of components being erected would be 19,000 kg (42,000 lb.). The lifting capacity is 30% less than that required for the precast concrete span, but the estimated fabrication cost was 165% the cost of the precast concrete span.

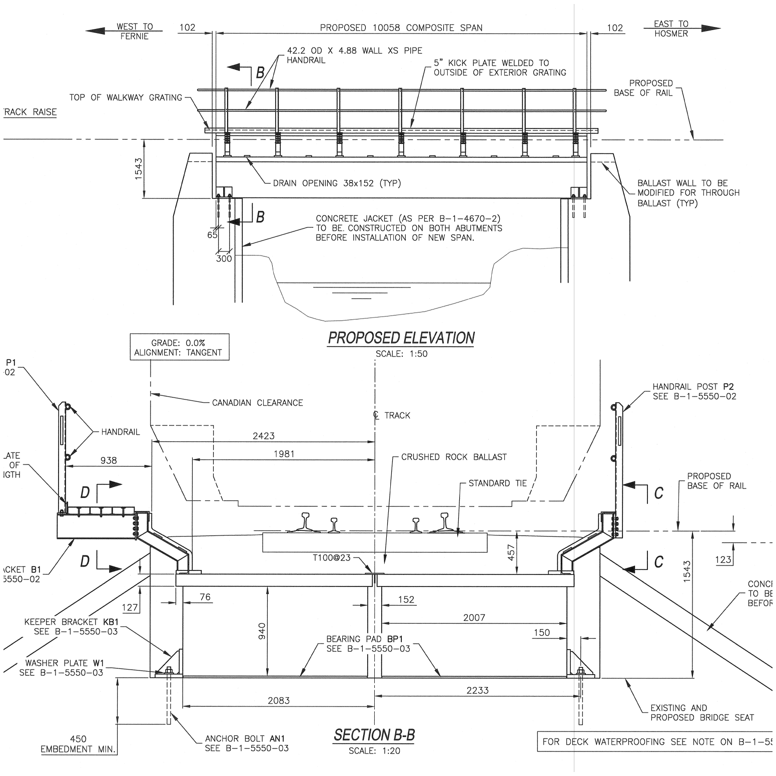

Figure 3.4: Cross section of hybrid-composite beam (HCB) span

None of the options required extensive modification to abutment bridge seat or track elevations, and the only abutment rehabilitation required was the construction of a concrete jacket to mitigate minor surface deterioration (Figure 3.5). The span replacement was to be performed by the railroad's experienced bridge maintenance and construction crews from Cranbrook, BC, using a 225-tonne (250-ton) locomotive crane. If the locomotive crane could not accommodate the lift, increased erection costs would be borne by the railroad using a contracted rail-mounted crane. Fabrication cost favoured the use of standard precast-prestressed concrete spans, but site constraints indicated the HCB span would provide for substantial savings in erection cost that would substantially exceed the difference in fabrication cost.

Therefore, constructability and overall cost considerations indicated replacement of the existing 1904 DPG span with a modern HCB span. This was achieved on October 22, 2014 with only a -10-hour interruption to rail traffic required to remove the 1904 DPG span and replace it with the HCB span (Figures 3.5 and 3.6).

Figure 3.5: Replacing existing deck plate girder span with hybrid-composite beam span

Figure 3.6: Completed installation of the hybrid-composite beam (HCB) span

Heavy-axle freight traffic continues to safely and reliably traverse Bridge 32.84 Cranbrook Subdivision, and further verification of performance by field measurement is planned in early 2015. The challenge was not to be the first railroad to install a HCB span, but to effectively replace a 110-year-old span. The challenge at this location was successfully achieved through the use of a modern HCB span.

4 ADDRESSING THE DURABILITY OF THE HCB

4.1 A Damaged Beam Becomes an Opportunity

A common concern raised regarding HCB bridges relates to durability and residual capacity if the beams are damaged or if there is any degradation of the components. After seven years of service performance of HCB bridges, there is no evidence of any deterioration, or any sustained damage to an HCB bridge. Subsequently, in the past, answering the question of durability could only be addressed through extrapolation of performance of other FRP products. Faith in analytical models can only allay concerns about performance of a damaged HCB for so long. Experimental data were warranted to fully understand the behaviour of these beams under less than perfect conditions.

It was only a matter of time until something would happen to an HCB bridge. As luck would have it, the HCB units for Bridge 32.84 were damaged in transit when they were shipped on a rail flat car to the bridge site in Fernie, BC. The two units shifted off of the hardwood dunnage and slid back and forth for an extended period during shipment. The abrasion against protrusions on the flat car resulted in significant damage to the FRP laminate on both units. One unit alone had nearly 18 individual gouges in the bottom, ranging from 1.2 m to 1.5 m long and 20 mm deep.

In recent years, bonding composite laminates to damaged concrete beams has become a standard method of repair of damaged beams. In the case of an HCB, these same systems can be employed, however with the simplification of bonding composites to composites, rather than composites to concrete. HCB, Inc. and CP worked together to engage Bay View Composites (BVC) out of Bellevue, WA, to mobilize to the staging location and sufficiently scarf out the damaged areas and bond additional layers of glass to fully restore the laminate to its original intended capacity. Once complete, the repaired beams were almost indistinguishable from the original condition as evident in Figure 4.1.

Figure 4.1. Before and after photos of repaired HCB unit

Fortunately, none of the steel strands were damaged on the HCB units for Bridge 32.84. Regardless, as pointed out earlier, since live load deflections typically govern design, there are generally additional steel strands as compared to what is required for the strength limit states. In recent testing at Virginia Tech, a 13.2 m HCB for a highway bridge was tested to determine the capacity of a beam with significant damage. The beam was compromised by cutting all of the laminate out of the webs at mid-span. 12 of the 22 strands at mid-span of the beam. Even with this extensive damage, this single beam was capable of sustaining 82,000 lb. of applied load before failing in bending. The magnitude of this load exceeds the 72,000 lb weight of an HL-93 design truck load. As a result, the residual capacity in the beam still exceeded the factored demand for the beam.

Additional lateral impact testing is currently underway at the University of Tennessee. On March 27, 2015 an impact test was conducted on one of the two units from the original railroad bridge tested at TTCI. The test apparatus comprised a 4,100 kg mass of concrete and steel accelerated down a ramp at roughly 30 degrees and impacting the HCB unit at the lower portion of center span. The mass derived for the test results in approximately 100 kJoules of energy equating to an equivalent static force of approximately 1,700 kN. The result of the first impact test was that the mass bounced off of the HCB bridge. Upon closer visual inspection, none of the steel strands were severed and the only apparent damage was cosmetic and could easily be fixed using the methods described herein.

Experience has shown that HCB bridges can sustain considerable Class 1 railroad live load traffic with no change in performance. It is also evident from the selection of the HCB for the Fernie, B.C. bridge, that there are applications where the HCB is the least cost alternative. In particular, in spans of 15 m to 21 m, concrete becomes too heavy and steel is too costly. This is an ideal range of span lengths for an HCB application. Further, it has been demonstrated that these beams can be satisfactorily repaired to their original capacity if damaged. Lastly, even with extensive damage, it is evident the HCB provides a safe and durable structure for any number of applications, including Class 1 Rail.

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