Footbridge over the Bow River in Banff

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Summary

Set over the Bow River in the mountain setting of Banff is a slender 113m long timber bridge both serving pedestrian traffic and providing a sensitive sanitary crossing replacement. Its minimal form was designed to blend into the natural beauty of Canada's first national park.

Completed in June 2013, the bridge was designed and constructed by StructureCraft Builders in collaboration with Fast + Epp Structural Engineers for the Town of Banff, under a design-build contract. Key to success of the project was careful attention to detailing, mitigation of dynamic behavior, and a high degree of pre-fabrication.

Figure 1 - Bridge superstructure after erection

Keywords: timber footbridge, long span, dynamics, tuned mass damper, design-build, Banff

1. Introduction

Given the highly visible and historically significant location, the client was very careful about the form the footbridge would take, the views it would create both from its deck and from surrounding vistas (of which it would form a part), the materials it would be made of, and the connection it would make with local trails. Driving the agenda, however, was a more pressing concern that existing sanitary pipes installed below the river at this location some fifty years earlier could fail, spilling raw sewage into the pristine Bow River. So the bridge also needed to carry new pipes, creating an important dual use for the new crossing. The bridge is designed to carry medium weight emergency vehicles, addressing another need in the community, as there is only one other crossing to the populated south side of the river. Being situated in a national park, environmental constraints were particularly stringent for both the final structure and the construction process.

In late 2011, the Town created a design-build competition attracting a number of respondents; choosing a winner who addressed the constraints, with a cost which fit within the budget. The final design features an 80m clear span, which for a timber bridge is one of the longest of its kind. This with a relatively slender 4m width create the primary design challenge for the bridge: its dynamic behaviour. Not uncommon with long span footbridges, the primary vertical and lateral frequencies fall directly in the range of susceptibility to pedestrian excitation. To sufficiently damp the response, several damping systems were investigated, with the final system comprising two custom-designed tuned mass dampers suspended visually with cables beneath the bridge. Monitoring of the structure in-place has allowed tuning of the masses to the measured natural frequencies of the bridge.

2. Design

The design-build delivery method enabled both the designers and the Town to pursue a variety of concepts based on a simple set of guidelines:

1. Design within a 135m crossing length, with maximum 5% slope for accessibility.
2. Carry two sanitary and one water line, critical for the Town of Banff.
3. Create a minimal, unimposing design.
4. Minimize work within the river channel.
5. Accommodation of medium sized emergency vehicles.

The structural system is simple: Propped by drilled piers located (to minimize disturbance) just outside the normal river channel, two 40m tapered haunch glulam girders cantilever from either side to support a central 34m suspended span. Tension rods tie the cantilevers down into concrete abutments at either end of the bridge. The bridge cross section comprises twinned sets of stepped glulam girders trussed with diaphragm steel webbing. These are designed to follow the flow of forces, and range in depth from 2.6m at the piers to 0.9m at the suspended span. The 4m wide path is made of solid timber panels which span between the tops of the girders, and are removable to provide access to the service pipes hidden below.

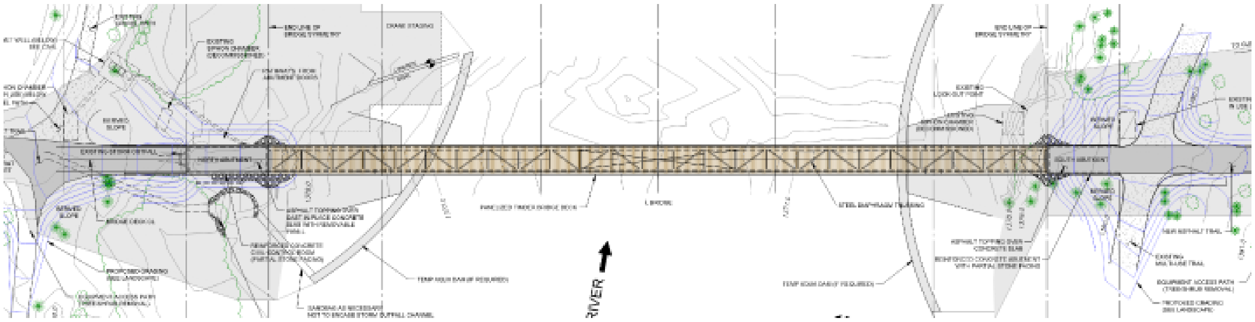


Figure 2 - Site plan

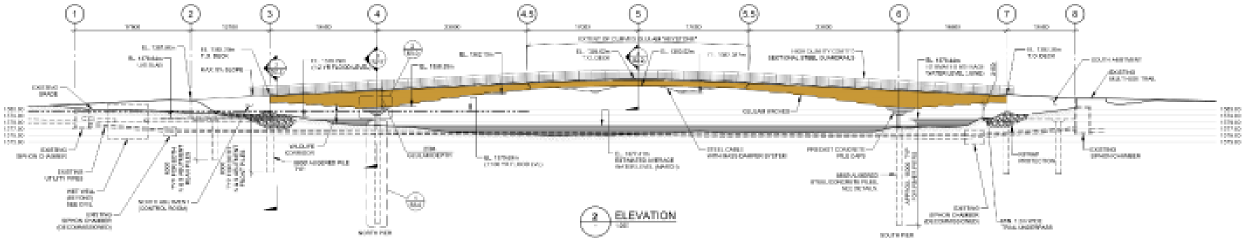


Figure 3 - Bridge elevation

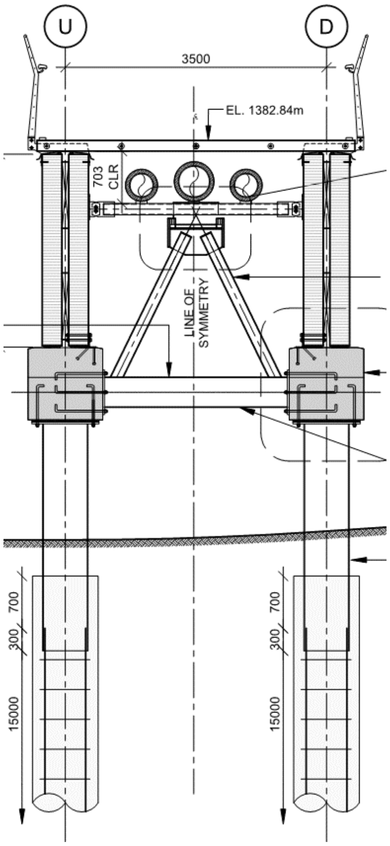


Figure 4 - Section at north pier

The concrete abutments at either end of the crossing build up the pathway to the bridge level, but also house the machine room for the mechanical systems required to run the lift station, eliminating the need for any additional above-grade structures. Thanks to careful positioning of the bridge, existing trails on both sides of the river were maintained without any substantial grade or alignment changes.

Piling in a national park and close to a township was a delicate process, requiring careful selection of foundations. Noise and soil constraints ruled out driven piles, and environmental restrictions within the river basin required the installation of a containment system around the entire piling area. The two sets of piles in the river take large compression loads, as the pivot of the cantilever, while the two front piles at each abutment hold down the cantilever's back-span. Each of the river piles has a steel pipe anchored to augured concrete piles and fastened to the precast concrete pile caps above.

The glue-laminated beams contribute to the bridge's character and natural feel, however wood beams of this scale are not without their challenges. At up to 2.6m deep, 43m long and 11.5T per piece, simply finding manufacturers capable of producing beams this big was a challenge. The girder supplier needed to perform a full survey of their own facility to ensure that once loaded onto a tractor and steerable rear axle rig, the beams with their stepped profile maintained adequate clearance leaving their yard.

Durability was a topic of significant interest to the client. The Town wanted to ensure that the bridge continued to look and perform well for the extent of its design life. A tremendous amount of energy was spent detailing for durability. The glulam pairs were separated by laminated veneer lumber (LVL) blocking and capped with a heavy gauge galvanized steel flashing. The spacing allows full ventilation between members and the flashing creates a drip edge shedding water 100mm from the face of the glulams. All steel components are hot dip galvanized (HDG) or stainless steel, and rubber spacers or grommets separate the two where they interface. The glulams were coated with a high quality system which behaves like a membrane, allowing vapour to pass through while preventing liquid water from penetrating the wood. A darker tint was selected to provide improved UV protection and all three coats were applied in shop prior to shipping. The town has committed to maintenance of the coatings with the goal of increased longevity and performance of the structure.

Figure 5 - Pile installation through the ice

Figure 6 – Concealment of service pipes

The steel diaphragm trussing serves a dual purpose, both connecting the pairs of glulam beams and creating support for the three service pipes sitting just underneath the bridge deck. Rollers are attached to the steel webs, allowing the pipes to be easily deployed across the bridge, and accommodating thermal movement of the pipes during the year.

Figure 7 - Drop-in span detail

The central drop span sits on neoprene bearing pads on notches in the receiving ends of the cantilevered Glulam beams. This detail is achieved by using long screws to reinforce notch. Diaphragm chord forces are transferred through the connection into the beams via steel drag straps along the tops of the beams, concealed beneath the deck panels and flashing. This forms an elegant, concealed connection which was easily assembled on site and left plenty of tolerance during erection.

3. Structural Analysis

The structural analysis and design of the bridge and associated abutments was in some ways relatively simple – as a determinate system, the basic forces in the cantilevers and drop span due to gravity loading can be calculated quickly by hand. To capture the more complex behaviour due to stepping of glulam, a finite element model was built incorporating the beams and pile caps as shell elements, and the trussing and piles as beam elements.

The long span and slender section of the bridge make it susceptible to both vertical and lateral excitation from human traffic on the bridge. The use of timber, which is less stiff than steel, also contributed to creating a more flexible structure. Early discussions with the client highlighted the fact that this was likely to be a lively bridge, and mitigation measures were proposed.

The 3D finite element model was also used to investigate the response of the bridge to dynamic excitation. Preliminary modal analyses showed that the fundamental frequencies of the bridge both vertically and laterally fell within the critical range for human excitation. The primary modes of concern and their natural frequencies were as follows:

Table 1 - Critical modes and frequencies

Mode Description	Predicted Frequency (Hz)	Measured Frequency (Hz)	Mechanism
First Lateral	0.8	0.8	Walking
Second Vertical	1.9	1.5	Walking
Second Torsional	3.1	3.3	Jogging

It seemed evident that some form of damping system would be advantageous for user comfort. Detailed dynamic loading models for each of the potential excitation scenarios were imposed on the finite element model, and analysis of the time history acceleration response provided the first estimates of performance under pedestrian excitation and the level of damping required.

Figure 8 - Tuning of mass dampers before erection

Several damping systems were investigated, including viscous dampers fastened to the bridge diaphragm, and combined viscous and tuned mass dampers suspended below the bridge deck. The final system adopted comprised two asymmetric custom-designed tuned mass dampers suspended on cables at quarter points beneath the central span of the bridge. The dampers were created using a cradle which had the capacity to hold different numbers of tuning mass plates. This cradle was suspended from the bridge above with two sets of cables, of particular lengths and stiffnesses.

4. Fabrication

A parametric 3D solids model of the entire bridge was created early on in the design process, allowing rapid and detailed investigation of a multitude of design decisions, providing visual feedback to both designer and client. The model grew through the design process to include every component of the bridge – from the surrounding topography to the giant glulam beams to the minimal guardrails. The parametric nature of the

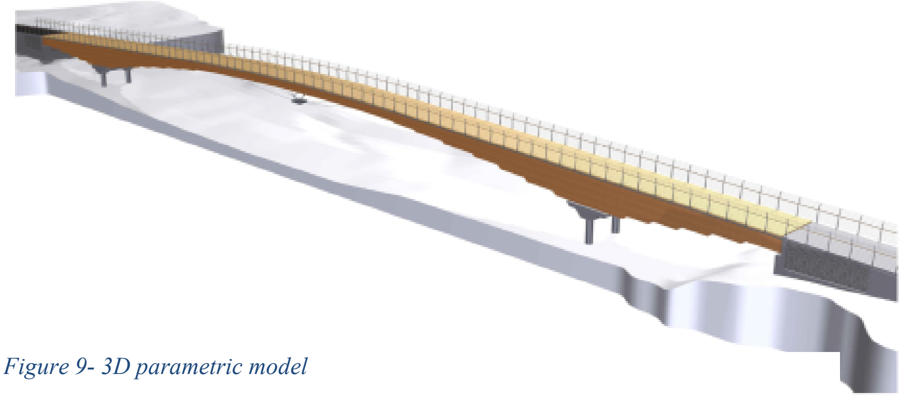


Figure 9- 3D parametric model

model allowed it to respond seamlessly to changes in global form and reflect them down to the smallest level of detail.

The model was critical to many parts of the design process, from early visualization and rendering, to cut-and-fill calculations on the site, trucking viability, and fine tuning the aesthetics of the tuned mass damper beneath the bridge. Most importantly the model was used to create detailed fabrication drawings for each piece of the bridge. The link between model and drawings ensured drawings remained accurate even as the design evolved.

As the Glulam beams are curved, the parametric model contained both 'states' of the beams – pre-bent (straight, prior to cutting) and post-bending (arched and cut to length), allowing accurate dimensional checks to be performed at each of the manufacturing stages and an accurate appraisal of erection weights.

Comprehensive part numbering and component scheduling within the model provided accurate material take-offs and ensured all pieces were assembled correctly on the site.

Fabrication of all timber elements occurred in the shop. The direct proximity of the fabrication shop and the design team allowed full-scale 'rapid prototyping' of many of the key components of the bridge. Handrails, stanchions, and deck panels all went through several mock-ups and design iterations before settling on a final design optimised for both form and aesthetic.

Throughout the design and fabrication process, the delivery model led to a natural desire to create efficiency: similar to the manufacturing industry, conceptualisation, design, modelling, testing, fabrication, and erection takes place in-house, allowing each step of the process to be influenced by the other steps.

Figure 10 - Glulam delivery at fabrication shop

5. Erection

A tight, remote site, huge structural elements, and harsh winter weather all combined to make the bridge erection a challenge. This, coupled with a desire to complete the lifts before spring thaw and a firm arrival date for a large mobile crane put a huge emphasis on ease and accuracy of assembly in the field.

The main structural elements of the bridge were too large to be transported to the site in modules ready for installation; and fitting up the pieces over the river with a smaller crane would have presented significant environmental and safety challenges. In order to accurately assemble and erect the bridge, the individual elements were prefabricated in the shop and shipped to site as a kit of parts. All cutting, drilling, sanding and finishing was performed indoors under controlled conditions so that members were protected from the elements both in transit and on site. Jigs were built to ensure accurate assembly of the main bridge components in the field. The stepped glulam girders were paired up and joined by long fully threaded screws through pre-drilled holes. Once the beams were levelled and squared to each other, the diaphragm webbing was connected with friction grip bolts to the receiving plates which were fastened to the innermost glulam face.

Figure 11 - Erection of south girders

During the final preparations for the big lift, temporary walking planks and safety lines were installed to provide immediate access to the bridge sections after installation. Additionally, several survey targets were installed to the girders, both at the abutment end and at the tips which would receive the drop-in span. This allowed real-time verification and placement of the bridge sections and fine tuning of the hold-down rods at the abutment ends to compensate for dead load deflection of the girders and the drop-in span.

Figure 12 - Erection of drop-in span

In all, the entire bridge superstructure was erected in 3 lifts over 2 days with an additional day spent relocating the crane to the North bank of the river. The tapered girder assemblies weighed in at over 50T while the drop-in span, complete with tuned mass dampers, maxed out the 500T crane at just over 20T and a radius of 45m. The bridge sections rested within 12mm of their target coordinates and the drop-in span “fit like a glove,” according to the erector.

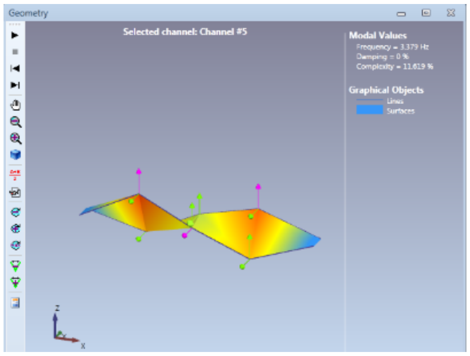
Figure 13 - Dropping over tie-down rods at abutment

6. Dynamic Testing

The desire for field testing of the bridge arose early in the design phase and gained traction as the importance of its dynamic behaviour came into focus. The testing was primarily required to provide experimental validation of the structure’s natural frequencies; but a number of additional tests were performed which provided estimations of modal damping as well as measurements of pedestrian induced accelerations for comparison with user comfort criteria. This information allowed for precision tuning of the dampers and quantification of their effect on user comfort.

A variety of tests are available to determine dynamic properties of structures, however, the Ambient Vibration Test stood out as the most appropriate and convenient method. Due to the current availability of high precision sensing equipment and sophisticated data analysis software packages, experimental modal estimation, which once required extensive equipment, custom software, and precise knowledge of the input forces and frequencies, can now be performed with a few accelerometers and a laptop. The test setup involves positioning of accelerometers at locations of maximum estimated modal displacement which are set to record simultaneous data sets of the accelerations measured under ambient vibration of the structure.

The testing of the Banff Bridge utilized a commercially available software package for the determination of the natural frequencies and associated mode shapes. The software applies local degrees of freedom to the global geometry where accelerometers are to be placed. Higher accelerations resulting from resonance at the structure's natural frequencies appear as peaks on a frequency vs acceleration plot, which made the modal frequencies easily identifiable. Finally, by selecting the peaks on the graph, the software animates the dominant motion of the structure as measured by the accelerometers. In this way we were able to visually confirm which mode shapes we were measuring and compare with the analytical model.



Frequency = 3.379 Hz
Damping = 0 %
Complexity = 11.619 %

Figure 14 - 2nd torsional mode (from AVT)

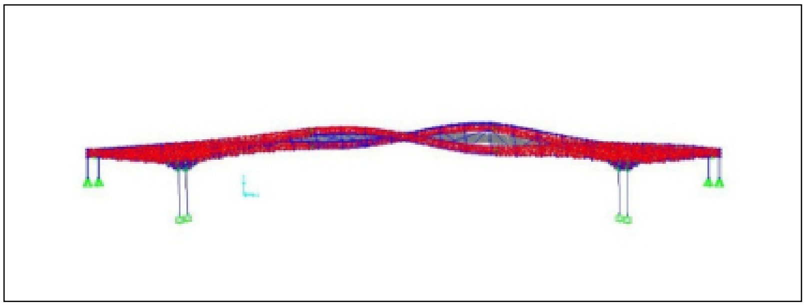


Figure 15 - 2nd torsional mode (analytical model)

Once the true natural frequencies were known, it was time to tune the dampers. Instead of simply tuning to the measured frequencies, baseline testing was performed to estimate the modal damping of the structure before and after tuning. Resonance tests, which seek to excite only specific modes, were performed by jumping up and down at the exact natural frequency of the mode being excited. With the assistance of a metronome, it was relatively easy to activate the modes of interest by jumping at a location of high modal displacement. Once resonance was achieved, the excitation was stopped and measurements of the free decay response were taken.

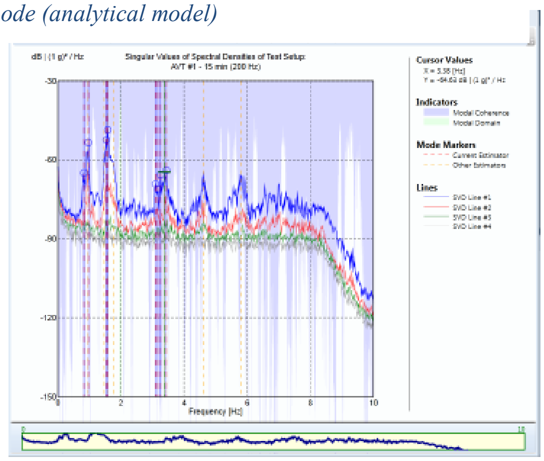


Figure 16 - Frequency domain decomposition graph

Estimation of modal damping was determined by fitting of an exponential curve to the free decay response according to equation (1).

$$a(n+1) = a(n)e^{-2\pi\xi\sqrt{(1-\xi^2)}} \tag{1}$$

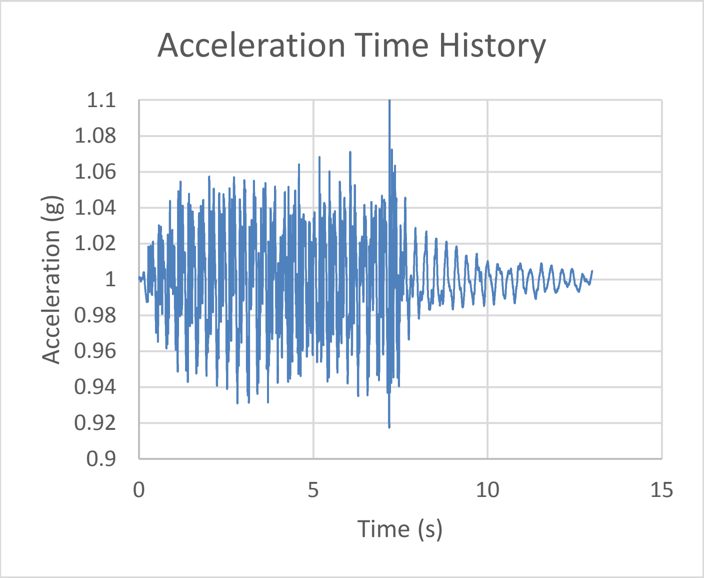


Figure 17 - Excitation and free decay of 2nd torsional mode

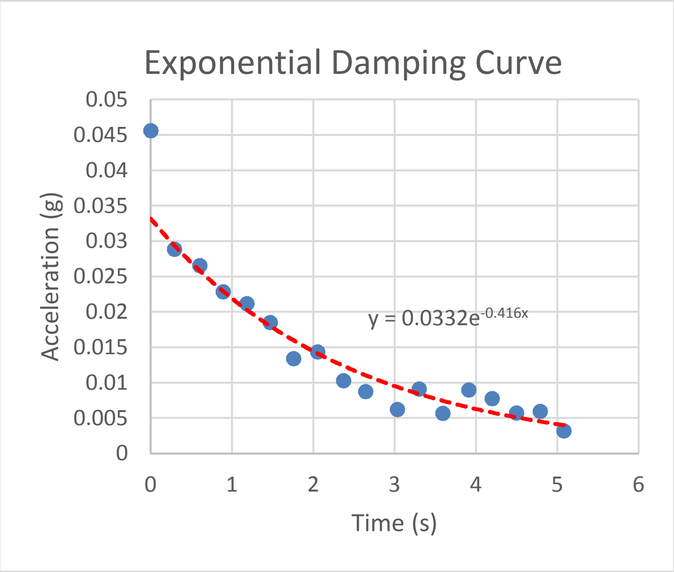


Figure 18 - Fitting of exponential curve to free decay response

Since the two tuned mass dampers were designed to mitigate motions excited by the 2nd vertical and 2nd torsional modes of vibration, these were of particular interest. The 2nd vertical mode was predicted to be at 1.9 Hz and the damper's vertical stiffness & mass were proportioned to have the same natural frequency with room to add or remove mass for tuning. The measured frequency of the 2nd vertical mode was significantly lower than anticipated at 1.5 Hz; meaning the structure was softer than predicted, likely due to uncertainty in modelling the boundary conditions. Frequency follows equation (2) and being unable to alter the stiffness provided by the

$$f = 2\pi\sqrt{\frac{k}{m}} \tag{2}$$

cables suspending the carriage, the mass needed to be increased by over 600 kg (or 60% of its predicted mass) for which we had made sufficient allowance in the damper carriage. By contrast, the 2nd Torsional mode was predicted to be 3.1 Hz and was measured at 3.3 Hz. This required an increase of only 50 kg to 375kg total. Once the masses of the dampers had been calibrated to the bridge's natural frequencies, an additional set of resonance tests was performed for both the 2nd vertical and 2nd torsional modes. The accelerations and structural damping were compared with the baseline tests performed before tuning.

The tuned mass dampers improve the dynamic performance by preventing the accelerations from reaching unacceptable levels by participating in and out of phase at the natural frequencies; thus preventing a resonant response. The results of the before and after tuning resonance tests showed that the damping ratio increased slightly but remained at a relatively low 1.5-2% depending on the mode under consideration. Vertical accelerations were reduced by over 50% to less than 1 m/s^2 during excitation of the 2nd vertical mode.

In order to calibrate the model to match the field tested frequencies, very small adjustments to suit the boundary conditions between the drop span and haunched girders as well as the bearing surface between the girders and the precast pier cap brought the analytical frequencies precisely in line with measured values. This sensitivity to actual site conditions is a major reason why there is a continued need for field testing of vibration controlled structures.

7. Conclusion

Footbridges are an excellent opportunity to exploit the use of timber, especially in beautiful settings. However great care in design and execution must be taken to account for its unique properties, and to ensure the structure will remain an enhancement to the setting which all can enjoy for many years to come. Proper credit goes to all involved, including a sympathetic client with great aspirations!

Figure 19 - Finished bridge south bank

Figure 20 - Finished bridge south elevation

Figure 21 - Opening day crowds

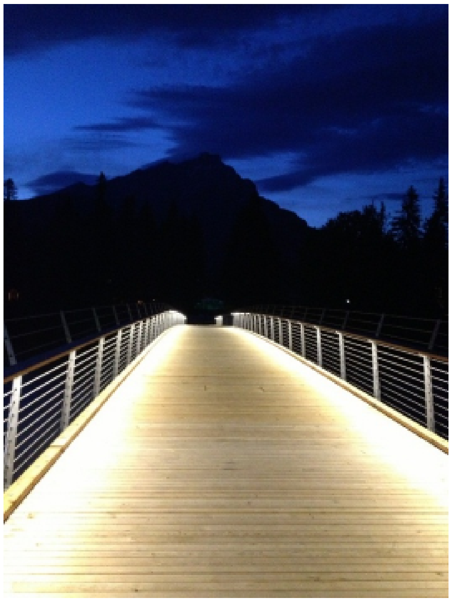


Figure 22 - Illuminated walkway