PROVENCHER CABLE-STAYED PEDESTRIAN BRIDGE

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ABSTRACT

An extensive public consultation process lead to Provencher Paired Bridges solution consisting of both vehicular and pedestrian bridge structures, to replace the existing Provencher Vehicular Bridge which had reached the end of its service life. Significant additional funding was secured to achieve this very attractive but more expensive solution to generally satisfy the requirements of the public, the Project Advisory Committee, and the City of Winnipeg—who were, together, the prime stakeholders for this project.

The new Provencher Pedestrian Bridge is a two-span, 200-m-long, 5-m-wide cable-stayed bridge that spans the Red River in the heart of downtown Winnipeg immediately north of The Forks, where the Red and Assinboine Rivers meet. The signature feature of the bridge is its transversely inclined pylon developed to provide a continuous walkway and to help balance the dead load forces. A 370-m^2 (400 ft^2) centre plaza is also supported off the pylon and provides additional dead load used to balance out some of the forces in the pylon due to its incline. Two pylon balance stays were also used to further reduce the unbalanced moments in the pylon. Aesthetics, personal safety, and lighting have been given high priority for this unique structure.

One major innovative focus is the structural health monitoring (SHM) which has been incorporated in the design throughout the pedestrian bridge structure, in association with ISIS Canada.

The design of the SHM system required the collaboration of a diverse group of engineers and provided a unique opportunity for engineering students at the University of Manitoba to participate in this state-of-the-art project. The performance of the cable-stayed bridge can be continuously monitored and evaluated using an interactive, remotely-monitored Data Acquisition System. The system incorporates fibre-optic sensors, conventional electric strain gauges, thermocouples 1-D and 3-D accelerometers, wind monitor, and inclinometers to measure strains, natural frequencies, temperatures, wind speed, etc. Looking to the future, this continuous monitoring of the bridge will help to optimize maintenance costs and minimize capital costs, resulting in savings to owners and ultimately the taxpayers.

INTRODUCTION

The new Provencher Pedestrian Bridge is a 5-m-wide, 200-m-long cable-stayed bridge that spans from the west bank to the easternmost pier of the new vehicle bridge. The main span of the bridge is 110 m long and the signature feature of the bridge is its transversely inclined pylon. The original concept was to curve the walkway around the pylon to balance the dead load forces. However, the curved bridge concept did not meet the PAC objective of restoring the alignment of the old Broadway Bridge. Therefore the walkway straightened out to meet this objective, but the PAC chose to retain the signature feature, thus an inclined design for the pylon was required.

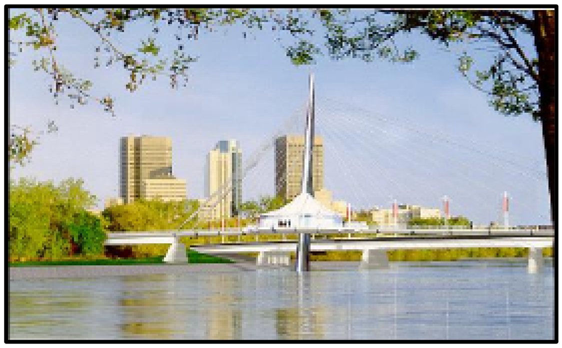


Figure 1: Provencher Pedestrian Bridge

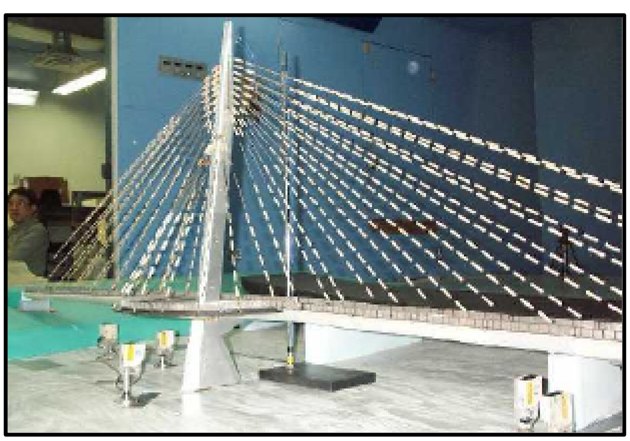
A 370-m^2 (4000 ft^2) semicircular centre plaza surrounds the southern portion of the base of the inclined pylon. The dead load of the centre plaza, along with two pylon balance stays were used to reduce the unbalanced moments in the pylon.

Through public consultation the design basis for the pedestrian bridge changed from being a simple pedestrian crossing to that of a place of meeting and gathering. The centre plaza is intended to house future economic opportunity for a restaurant-type business that would become the focal point of the bridge. In addition, plazas at both the west and east ends have been provided for further opportunities. In particular, the east end features a plaza that is similar in size to the centre plaza that was constructed with the vehicular bridge contract. Based on the intended use, a rigid deck system was developed to provide a high level of pedestrian comfort.

This paper will discuss some of the key innovative engineering design issues that were addressed throughout the design of the pedestrian bridge. These include the wind study, the design of the pylon, the construction of the pylon, the structural health monitoring, and the bridge architecture.

WIND STUDY

The design process began with an extensive analytical study to determine a cross section for the bridge deck that provided the best combination of flexural and torsional stiffness as well as mass. Working with RWDI, the wind tunnel subconsultant, the final section dimensions were determined and tested for aerodynamic characteristics. Once the section properties were finalized, a 1:60 scale aeroelastic model was constructed to determine the overall structure behaviour subjected to wind loading.



RWDI performed a study to determine the topographical situation, proximity to other tall structures, climatic data, ice accretion accumulation, and design wind speeds. Once the model was constructed, the behaviour of the bridge subjected to wind was determined and compared back to the structural mode shapes of the bridge. From this we could determine what the most critical wind speeds for the bridge were and that the structure was stable.

Figure 2: Aeroelastic Model of the Bridge - Elevation

The wind tunnel testing considered the fully erected bridge, as well as the construction sequencing of the bridge. This aided in determining the most appropriate erection sequence for the pylon prior to any stays being erected.

The pylon pier which is the section of the pylon below the deck, is founded on an elevated footing supported by 12 large-diameter, steel-jacketed, rock-socketed caissons. The pier shaft is reinforced concrete and is architecturally shaped to enhance the transfer of forces from the pylon and the bridge deck into the footing. The geotechnical information obtained indicated that this combination would provide the most economical solution.

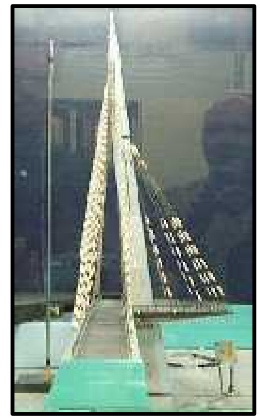


Figure 3: Aeroelastic Model – Side View

DESIGN OF THE PYLON

The Provencher Pedestrian Bridge designers were innovative in their approach in dealing with massive moments at the pylon base (Figure 4).

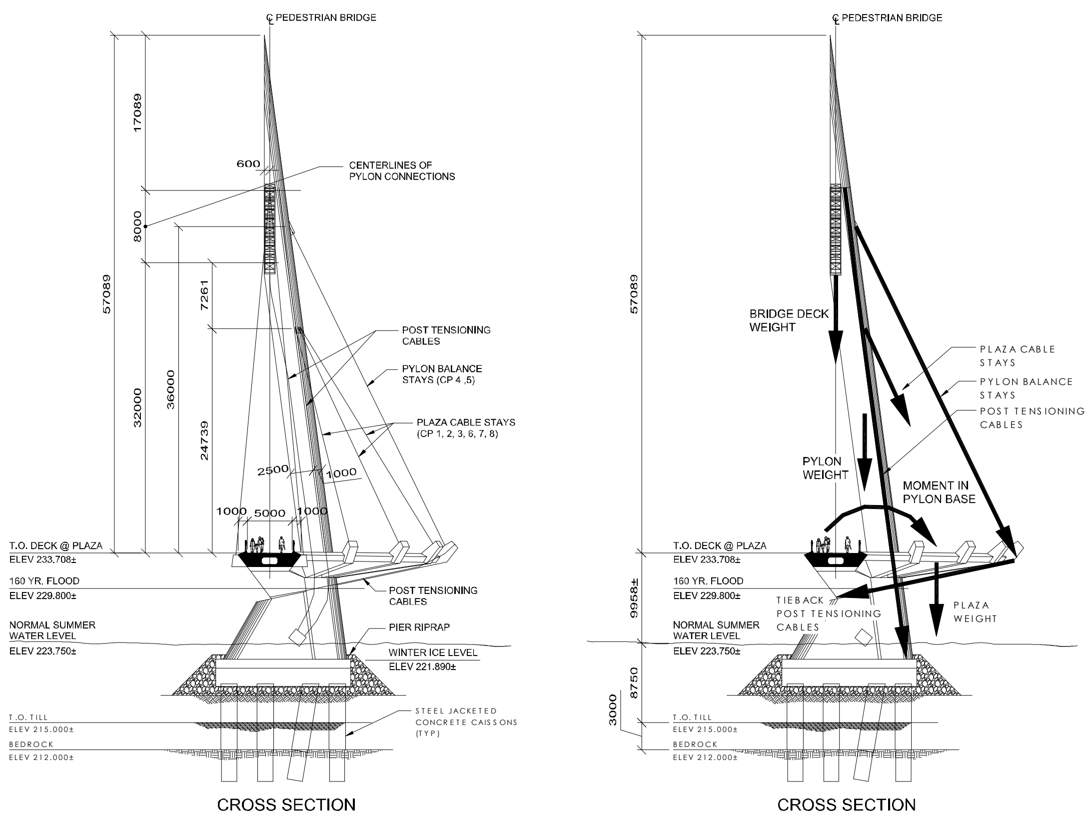


Figure 4: Bridge Pylon – Description of Load Transfer

Due to the nature of cable-stayed bridges, and to the fact that this design incorporates a single pylon support structure, the pylon attracts all the dead loads of the entire walkway. This includes the over 57-m-tall steel-jacketed concrete pylon self weight and the 370-m^2 reinforced concrete centre plaza. Since the pylon is inclined, massive moments are induced into the relatively narrow pylon, even though the centre plaza counteracts a small percentage of the moments. To achieve the required resistance while keeping the slim pylon shape, two major design innovations had to be incorporated in the pylon: 1) Additional pylon balanced stays pivoted about the centre plaza; and 2) Posttensioning within the pylon structure.

CONSTRUCTION OF PYLON

Another challenge was to temporarily support the staged pylon during construction (Figure 5).

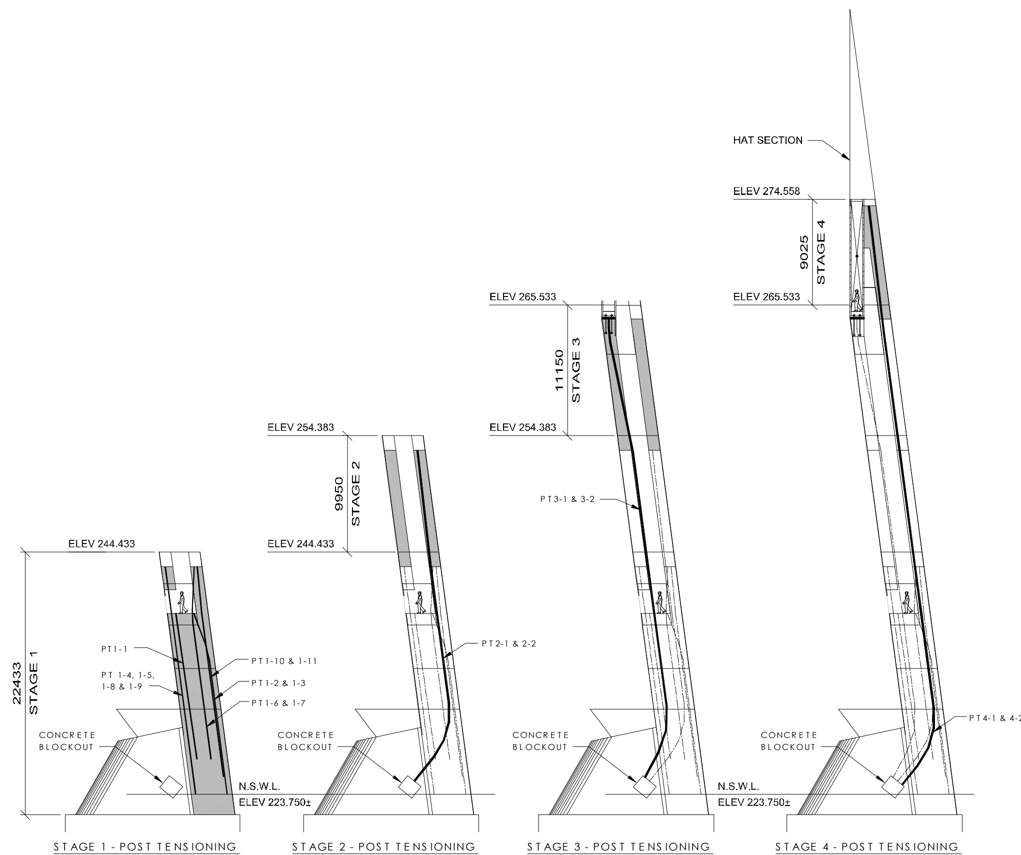


Figure 5: Schematic Description of the Pylon Construction

Stage 1 of the construction of the pylon starts with the connection of the first steel jacket segment to the concrete pier structure. Ducting to accommodate posttensioning ducts, which includes high-strength steel bars and cables, to both the pier and the proceeding pylon segment are placed within the steel jacket, and the segment is filled with concrete. The top of the first pylon segment has an internal manway formed within the concrete, which is approximately 1.0 m x 1.5 m, to allow for future inspections within the pylon and access to the top cable-stay anchorages. PT-1 cables are then stressed to provide additional strength to the pylon.

The second stage includes the placement of the second pylon segment on top of the first segment, and additional posttensioning ducts are installed. Once the concrete is poured within the steel jacket, both segments are posttensioned to each other and to the pier through all the PT-2 cables.

The third stage includes the placement of the third pylon segment (including concrete and steel jacket) and the posttensioning of all PT-3 cables which are anchored into the pier provides additional moment capacity during the construction prior to the off-setting centre plaza structure being installed.

The fourth stage includes the placement of the fourth pylon segment (including concrete and steel jacket), the posttensioning of all PT-4 cables (which are anchored into the pier, providing additional moment capacity for the final pylon structure), and the installation of the last section.

STRUCTURAL HEALTH MONITORING

Structural Health Monitoring (SHM) is an evolving technology that can monitor and define the health of emerging innovative civil engineering infrastructure. Civil infrastructure systems are generally the most expensive assets in any country (an estimated $2 trillion in Canada), and these systems are deteriorating at an alarming rate. The introduction of innovative design approaches in these systems is painfully slow due to heavy reliance on traditional construction and maintenance practices, and the conservative nature of design codes. Feedback on the “state of health” of constructed systems is practically nonexistent. d,” and many are in a state of disrepair due to inadequate maintenance, excessive loading, and adverse environmental conditions.

SHM techniques originated in test laboratories and were used to examine the behaviour of structural samples. The technology has been introduced into the engineering practice over the past five years. It has been incorporated into several projects including the collaborative work of Wardrop and ISIS Canada on the Taylor Bridge in Headingley, Manitoba (http://130.179.134.168/Taylor.html), which was the first structure worldwide to be remotely monitored via a telephone line. The Provencher Pedestrian Bridge project has taken this technology to the next level. It incorporates some of the most comprehensive applications of the SHM technology to date.

Taxpayers will benefit from the cost savings associated with the continuous monitoring capabilities and early problem detection opportunities. The goal of SHM on this project is to develop and prove out the use of this technology and be used as a real and effective tool by bridge owners. We are optimistic that this technology will result in extension to the life of the bridge and therefore result in cost savings.

The Provencher Pedestrian Bridge is the City of Winnipeg’s first cable-supported structure. Performance of the bridge will be continuously monitored and evaluated using the state-of-the-art structural sensing technology. Wardrop has designed the SHM system with a nerve network consisting of the sensors and a brain represented by the Data Acquisition (DAQ) system. Several types of sensors are used, including 18 fibre optic sensors, 30 electric strain gauges, thirty thermocouples, 19 unidirectional and 4 tri-axial accelerometers, a wind monitor, 14 electronic inclinometers, and a web camera. The DAQ system resides in the west abutment and will be connected to the World Wide Web via a high-speed cable modem.

Sensors Description

The intent of SHM system is to provide feedback on the behaviour of the bridge as a whole and on the performance of the cable stays, the pylon, the deck, the bearings, and the abutments. Table 1 summarizes the different types of sensors and their location on the bridge.

Abutment and Bearing Movement

The relative movements of the abutments and the bearings will be measured using RockTest tilt-beam sensors, mounted on a 2.5-m arm. The movement of the bearings is expected to vary daily, while the abutments' movements will not have such a frequent variation. Therefore, the inclination of the abutment will be measured using the direct reading of the tilt-beam sensor (shown in Figure 6) to give an indication for any unfavourable motion, while any horizontal or vertical movement will be quarterly measured using a toll station. The angle of deviation, $\delta\theta$, of the arm from its original position will be recorded by the tilt-beam sensor and transformed to a displacement, $\Delta_{bearing}$, using the following equation: $\Delta_{bearing} = 2500\ \delta\theta$ (mm)

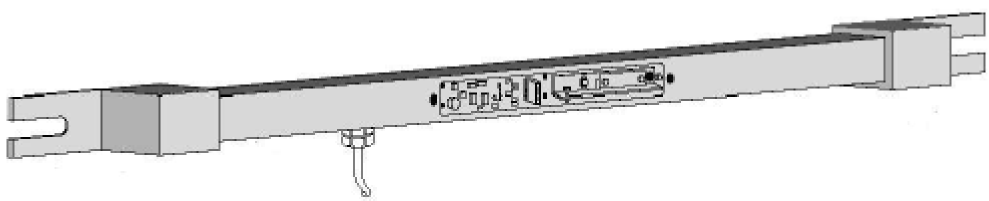


Figure 6: Tilt-beam sensor

The bearings of the vehicular bridge (which is built north of the pedestrian bridge) are monitored in a similar way and wired through the DAQ system on the pedestrian bridge.

Pylon Sensors

Thirty electric strain gauges and eighteen fibre-optic sensors are installed at critical elevations along the pylon, including:

- The pylon-deck junction
- Plaza stay-cables' connection to the pylon
- Main stay-cables' connection to the pylon
- Intermediate locations

A crossbow tri-axial accelerometer (shown in Figure 7) and a RocTest tilt-beam sensor are installed at the upper tip of the pylon to measure the pylon's vibration and inclination.

Each strain gauge or fibre-optic sensor is bonded into a steel strap that is spot welded to the steel bar or the steel plates reinforcing the pylon. This installation methodology will optimize the amount of time needed to install the sensor on-site. Thermocouples are installed close to the strain gauges to provide temperature compensation for the strain readings.

Figure 7: Crossbow triaxial accelerometer

Stay-Cable Sensors

Several unidirectional accelerometers are installed on the plaza stay-cables and the main stay-cables to measure the vibration of the cables when the bridge is subjected to wind loading. The vibration measurements will be used to estimate the cable force using the method established by Zui H., Shinke, T., and Namita, Y. ("Practical Formulas for estimation of cable tension by vibration method," Journal of Structural Engineering, ASCE, Vol. 122, No. 6, pp. 651-656.)

Deck Sensors

Tri-axial and unidirectional accelerometers are installed at three locations along the east side of the deck and two locations along the west side of the deck. Measurements of the accelerometers will provide information about the frequency and the mode shape by which the deck is oscillating under severe wind conditions or any unacceptable man-induced vibrations. A wind monitor is installed at the deck level to measure the wind speed associated with the measured bridge vibration characteristics. A wide-angle web camera (shown in Figure 8) is also installed on the pylon to monitor the traffic flow on the bridge. The vibration information is necessary to maintain and upgrade the bridge damping system when needed.

Figure 8: Wide angle web camera

Thermocouples are also installed within the cross section of the bridge deck, to measure the temperature variation across the section and subsequently calculate the corresponding thermal stress in the bridge.

Data Acquisition (DAQ) System

The main DAQ system is placed inside a weatherproof heated enclosure, located in the west abutment. Another DAQ subsystem is installed inside the deck at the pylon and is connected to pylon sensors, the east deck sensors, and the east abutment sensors. All other sensors were connected to the main DAQ system. This arrangement was intended to limit the length of wire between the sensor and the DAQ system to 100 m. This limit applies to the electric sensors to prevent any signal loss while being transmitted to the readout unit at the DAQ system. The wires from the sensors to the DAQ system are pulled inside over 800 m of conduits. The two DAQ systems are made of National Instrument electronic boards and will be assembled by Wardrop with the help of the graduate students at ISIS Canada. The main DAQ system will be connected to a resident computer that can be accessed by Wardrop and the City of Winnipeg engineers using a high-speed Internet connection.

An independent fibre Bragg grating readout unit is placed in the west abutment and connected directly to the fibre optic sensors installed inside the pylon. This unit is provided by ISIS Canada as a parallel system to the conventional SHM system. The fibre optic system offers a series of unique advantages over their conventional electronic counterparts including stability, electromagnetic immunity, low transmission loss and resistance to corrosion.

Sensor Installation

The sensors have been installed on the various structural members during the construction of the bridge without affecting the critical path of the project schedule. This challenges the construction scheduling from the contract administration's point of view. It was a challenge to overcome sensor installation concurrent with construction activities for the different sections of the pylon (shown in Figures 9 and 10).

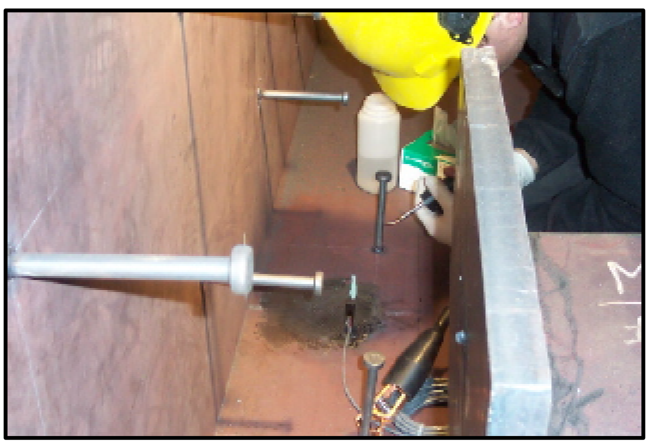


Figure 9: Installation of sensors

Figure 10: Wiring the sensors to the junction box before concrete pour

SOCIAL/ECONOMIC IMPACT OF THE SHM SYSTEM

The continuous monitoring of the bridge will assist the City of Winnipeg's engineers to optimize the bridge maintenance budget over the estimated service life of the structure. With this state-of-the-art technology the City may be able to identify problem areas more quickly than by traditional methods, so that they can be cost effectively resolved in a timely manner. The goal is that this technology will result in long-term savings to the maintenance budget.

As well, the project provided great opportunity for engineering students at the University of Manitoba to participate, through the ISIS Canada and NSERC programs, in a state-of-the-art project that incorporated the application of leading-edge technology.

COMPLEXITY OF THE SHM

In addition to the complexity of the sensor installation noted above, the design of the SHM system for the Provencher Pedestrian Bridge required the collaboration of a diverse group of engineers and provided a unique opportunity for engineering students at the University of Manitoba to participate in a state-of-the-art project. Performance of this cable-stayed bridge will be continuously monitored and evaluated using the interactive, remotely-monitored DAQ.

Table 1 - Different Types of Sensors and their Location on the Pedestrian Bridge

Response to be Measured	***Equipment***	***Mounting Location***
Measurements of Movement of the Deck, Abutments, and Top of Pylon		
West pedestrian bridge abutment	Two high-precision inclinometers	Inside on the backwall
West and east pedestrian bridge bearings	One low-precision inclinometers, mounted in stainless steel tubes with a hinge on the bottom	Beside the unidirectional bearing on the ped bridge support and beside the multidirectional bearing on top of Pier No. 4
Pedestrian bridge pylon	One high-precision inclinometer	Inside the top piece of the

Table 1 - Different Types of Sensors and their Location on the Pedestrian Bridge		
Response to be Measured	***Equipment***	***Mounting Location***
		pylon
Traffic flow on the bridge	One camera in heated weatherproof enclosure	North face of the pylon (180 degrees)
Wind speed and direction	Wind monitor	Beneath the deck on the west span
Stay forces	Unidirectional accelerometers	North and south stays
Pylon strain	Electrical strain gauges	Six gauges at five locations
Temperature Measurements		
Ambient temperature of the surface of the pylon	Thermocouples	At mid-height of the pylon
Temperature gradient within the deck section of the short span	Thermocouples	Embedded inside the midspan section
Temperature gradient within the deck section of the long span	Thermocouples	Embedded inside the midspan section
Vibration Measurements		
3D acceleration measurement of the centre plaza	Triaxial accelerometers	Attached to the outermost surface of the ring beam
3D acceleration measurement of the long-span deck	Unidirectional accelerometers	Attached to the outermost three sections of the east side of the deck
3D acceleration measurement of the long-span deck	Triaxial accelerometers	Attached to the surface of the mid-section of the east side of the deck
3D acceleration measurement of the short-span deck	Unidirectional accelerometers	Attached to the surface of the mid-section of the east side of the deck
3D acceleration measurement of the short-span deck	Triaxial accelerometers	Attached to the surface at a section of the west side of the deck
3D acceleration measurement of the pylon	Triaxial accelerometers	Attached to the surface at the top of the pylon

BRIDGE ARCHITECTURE

As engineers we sometimes do not appreciate the softer side of our designs. Aesthetics and bridge architecture is becoming more and more prevalent in our structures. The City of Winnipeg has moved beyond cold “utilitarian” structures and adopted a vision of design that respects aesthetics and beauty, and is willing to invest significantly to that end. This project had significant input from architects and the following design philosophy for the Provencher Paired Bridges project resulted:

> *“The paired bridge was designed to redress a wrong that came about when, in the midst of social and ideological disaccord, the City of Saint-Boniface and the City of Winnipeg invited the CN Railway to establish itself on the continuous formal boulevard which, west of the Red, was called Assiniboine and east called Provencher. This act forever severed the physical linking of the two Cities and put an end to the grand roadway.*
>
> *The pedestrian span not only reestablishes the exact line of the once grand boulevard, but it also provides an all-season gathering and event place on the plaza along its span. The cable-stay system is meant to reflect the light nature of its pedestrian traffic, while the spire, at the main plaza signifies a place of meeting in the middle of the Red River. All of the structural elements rise to this one focal point as its shining spire does not try to impose a new style of architecture for the river, but rather reflects the richness which surrounds it. It is a reflection and celebration of the many cultures which have always come together along these historical banks. As in days gone by, commerce and festivities are the order of the day. The location of a large multipurpose gathering plaza and commercial kiosks will bring people together and will be a first for any North American bridge. Another plaza located at the east end of the span serves to move people along the pedestrian span and encourages tourist traffic between Saint-Boniface and The Forks.*
>
> *While both vehicular and pedestrian spans are designed to reflect their purpose, they also share basic elements which make them two interpretations of the same idea and that idea is to reflect opportunity and a spirit of cooperation of two communities.”*

Bridge plazas truly separate this pedestrian bridge structure from the rest. The development of three plaza areas, shown in the plan view below, provides opportunity for pedestrian activities and programming so that this bridge acts as a destination as well as a link. These plaza areas are:

- The centre plaza created around the pylon mid-river. This plaza will have services and an enclosed area to permit a restaurant or other business.
- The west landing will link to The Forks pedestrian system and the pedestrian system being developed on Pioneer Avenue. It will provide open areas suitable for programming or temporary services (e.g., vendors) and an area for potential future building.

- The east landing will link to Provencher Boulevard and Tache Street and provide a connection to the riverbank and a proposed CAR-RAC dock. It will also provide open areas suitable for programming and temporary services.

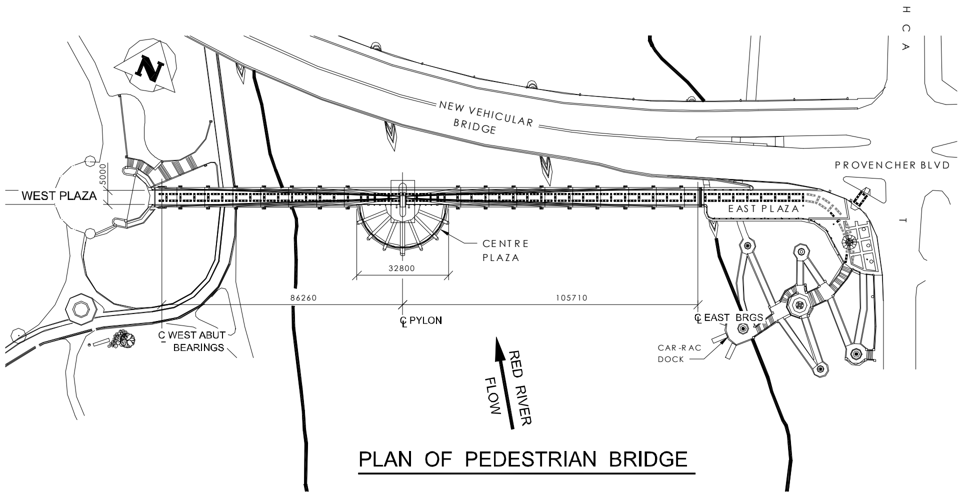


Figure 11: Overview of the Bridge Site

Lighting

Considering that this structure is located in the heart of downtown Winnipeg and will be a focus of hundreds of thousands of tourists annually, heavy emphasis was given to the pedestrian bridge lighting. The lighting philosophy was based on the use of indirect and hidden light sources to provide indirect illumination of major bridge elements while using the light spillover to provide a safe yet low-glare pedestrian environment. There are a number of lighting sources/types which focus on various aspects of the bridge. Various projectors mounted at hidden locations on the bridge light the following specific areas:

- north side of the top of the pylon
- north side of the base of the pylon
- the interior centre plaza structure
- the cable system of the centre plaza
- the cable system of the walkway, mounted at each cable anchoring point
- the walking surface

The lighting design was based on the following four major principles:

1. Indirect illumination of bridge elements
2. Personal security
3. Visibility without glare
4. Vandal resistance

Figure 12: Nighttime Lighting of the Bridge

Indirect Illumination

Indirect illumination is a technique which is somewhat unconventional in its application. Traditional lighting promotes presence of the source of light and by that fact, identification of its source. Its purpose is to directly light an object or surface. Indirect lighting hides the source and lights a specific and targeted object. The light cast from the reflection of light off the surface of the object provides the principle source of illumination.

Personal Security

The design does not allow for any hiding areas on the bridge and promotes long vistas and views. This fact allows for a very high level of visual penetration onto the site from various locations on and around the bridge system. Bollards are used as a balancing light source along the pedestrian walkway. The bollards provide a minimum general light level for this surface, while their downshining quality does not create undue glare and does not compete with the lighting at higher levels along the pylon's surface. These levels are derived from measuring only the output of the bollards on a standard grey concrete surface. The lighting levels are then complemented with light spill from the various sources. These sources include light that is projected from the sources mounted at each cable connection and which will bounce light off of the white cable casings along the entire length of the bridge. Using Medusa White cement in the concrete topping for the pedestrian surface will further raise the lighting levels.

Visibility Without Glare

The purpose of using indirect lighting sources throughout the bridge is principally to create a safe, yet welcoming (nonhostile) environment. This approach has two major benefits. Firstly, it does not shine light back to the person's face which would otherwise cause spot blinding and visual disorientation. The second benefit is that aggressive and targetable sources encourage reaction or vandalism. This is a common reaction to light being projected in one's face. By removing both direct presence and access to the source, vandalism is much reduced.

Vandal Resistance

The design promotes the three following levels of vandal resistance:

1. If the light sources are largely indirect, vandals will not be attracted to them and are far less likely to try and vandalize them. All light sources on the pedestrian bridge are indirect.
2. For any projector which may be visible, they are put in inaccessible locations. An example of this is that the cable lighting projectors are mounted on the outboard (over the river side) of the cable connection to the bridge surface. This connection is also located beyond the handrail of the bridge.
3. For any source that is accessible, it is placed in a secure environment, is an item which is designed to be in the public domain and is an item which has a high vandalism-resistant construction. The best example of this is the bollard, which is very robust in its construction, well protected within the handrail system, and an item designed to be used in high-traffic public spaces.

Surface Treatment

The surface is treated with a technique called concrete stamping. It is a technique by which a rubber stamp is tamped onto a green (partially set) concrete surface to create an imprint or pattern. This technique creates grooves or impressions which are approximately 1/8 inch deep. This feature has two positive effects. Firstly, it acts as an orientation texture for the for the cognitively challenged. This provides warning or edge as well as creating distance markers and travel gauges. It is however not deep enough to redirect wheeled vehicles such as strollers or wheelchairs. It is a multimodal-friendly surface. The second benefit is that it does act as a speed suppressor similar to rumble strips or speed bumps. When bikes, skateboards, or other wheeled vehicles pass over them at high speeds, they create enough vibration to encourage the rider to slow down.

The surface treatment also has an aesthetic component. The pattern incorporates a series of medallions. The medallions relate to ancient button holders on uniforms or formal dress. This allows the pattern to form a link with the sash form of the granite band.

Personal Safety

The plazas and landings, pedestrian bridge, and north sidewalk are being carefully reviewed for safety and accessibility. Elements that enhance safety will include:

- appropriately graded ramps
- railings allowing clear sight lines
- nonreflective materials minimizing glare that could obstruct views
- increased lighting levels

- properly trimmed landscaping and rounded corners, eliminating hiding places
- easily cleaned surfaces, minimizing graffiti
- security patrols
- safety devices such as telephones
- emergency vehicle access
- comfortable, easily maintained furnishings encouraging high use

CONCLUSION

For all stakeholders involved in the Provencher Pedestrian Bridge, it has been challenging but very rewarding. We note that although we have highlighted the wind study, the design of the pylon, the construction of the pylon, the structural health monitoring, and the bridge architecture, there were other innovations that were developed during this project. These include the deck posttensioning, the west abutment rock anchors, and the east plaza connection, among others. Overall, the Provencher Pedestrian Bridge is a very unique project that has developed into a community effect that produced a social, functional, and aesthetically pleasing gathering point in the middle of a major city. Innovation was the cornerstone for the success of this project—for all stakeholders.