Means Protection Barrier – Burgoyne Bridge

Brent Archibald, P.Eng.
Technical Director – Structures
Parsons Inc.

Frank Tassone, C.E.T
Associate Director - Transportation Engineering
Niagara Region

Andrew Luk, M.Eng., P.Eng., PMP
Senior Structural Engineer
Parsons Inc.

Sardar Nabi, M.S, P.E., P.Eng.
Manager – Transportation Structures
RVA (formerly Parsons Inc.)

Colin Zilstra, B.A.Sc., E.I.T.
Structural Designer
Parsons Inc.

Paper prepared for presentation at the Transportation Structures session of the
2021 TAC Conference & Exhibition

ABSTRACT

High-level and landmark type bridges have been found to pose as an opportunity for the vulnerable in society to die by falling which can have a significant impact on roadway users and the general public who witness such events. Typical bridge railings and parapets, while providing protection to the general public as users of bridges, do not provide sufficient protection against intentional falls from a structure. This paper outlines the planning, design, and construction of a means protection barrier system installed on the recently replaced Burgoyne Bridge in St. Catharines, Ontario, Canada. The Burgoyne Bridge replacement was completed in 2017 and spans over Twelve Mile Creek and Hwy 406. The 125m main span utilizes a tri-chord steel arch flanked by twin decks each supported by a single composite trapezoidal steel box girder. Each deck carries one lane of traffic, a bicycle lane, and a sidewalk and are separated with a median gap of 5.5m running the full length of the 333m long bridge.

The barrier for the exterior edges of the bridge consists of a unique inclined cantilever aluminum pipe picket type barrier, while the gap between the bridge decks is protected by a stainless-steel mesh netting system. Both barriers utilize the existing pedestrian railing post anchorages in an effort to both minimize impacts to the existing structure as well as expedite construction and reduce costs and materials. While visually noticeable, both barriers were designed to be sympathetic to the overall architecture of the bridge with the aim to not detract from the overall presence of the structure.

This paper will discuss the current state of practice across Canada and the Unites States while highlighting the design parameters and testing developed for this project to ensure its successful performance. In an effort to fully understand the performance during service of these barrier systems, wind tunnel testing and dynamic analysis of the barriers and structure were carried out for various wind loading conditions, resulting in the need for a damper solution to be utilized to reduce vibrations. This paper will also summarize the design decisions and lessons learned during the preliminary design through to construction of the Burgoyne Bridge means protection barrier system. These barriers present a unique solution harmonious to the overall architecture of the bridge with the expectation that they will provide reliable protection for the St. Catharines community and general public for many years to come.

1.0 INTRODUCTION

1.1 BURGOYNE BRIDGE

The Burgoyne Bridge is located in the City of St. Catharines and carries Regional Road 81 (St. Paul Street West) over Twelve Mile Creek and Highway 406. Construction of the 333-meter-long structure was completed in September 2017 and replaced the original Burgoyne Bridge which was constructed in 1915. The bridge serves as an important link between downtown St. Catharines and the western portion of the city and is oriented in the north-south direction. The bridge is comprised of seven spans with the 125m main span being supported by a centrally mounted steel tri-chord arch. The bridge is supported on reinforced concrete abutments and piers sitting on reinforced concrete caisson foundations. Figure 1 shows the general plan and elevation arrangement of the Burgoyne Bridge.

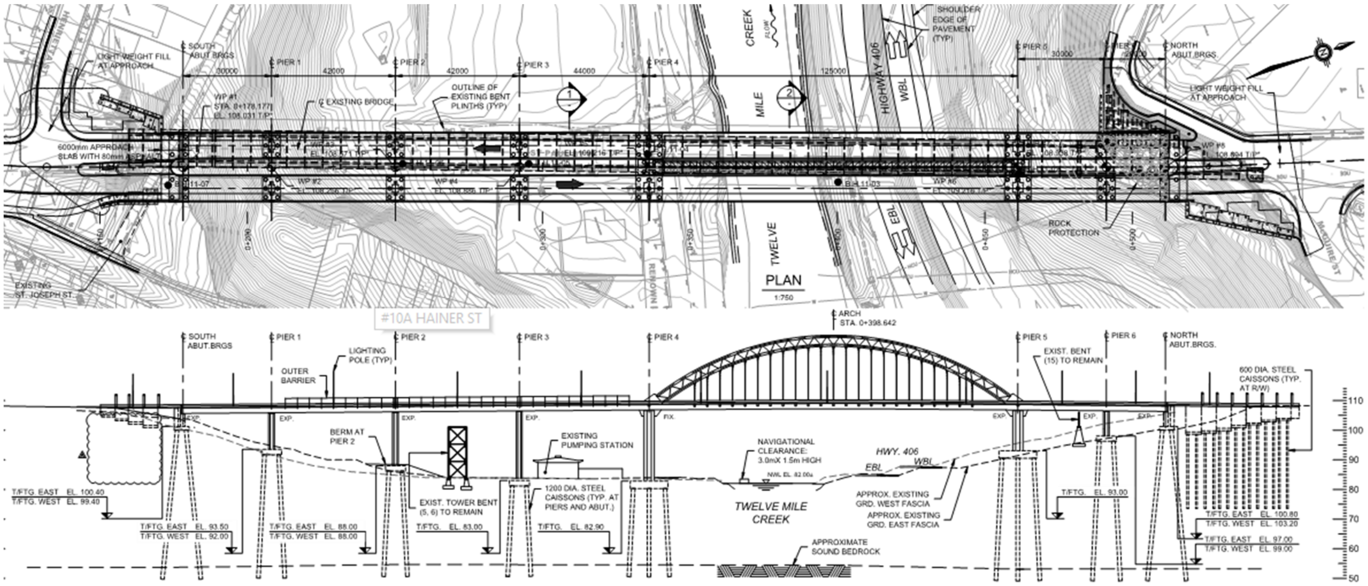

Figure 1 – Burgoyne Bridge Plan and Elevation

The bridge is comprised of a twin-deck structure making use of 2 parallel continuous composite trapezoidal box girders running the full length of the bridge. Each deck consists of 0.3m wide parapet walls, a 2.4m wide sidewalk, a 1.6m bike lane, a 3.5m traffic lane, and a 0.9m wide shoulder. The northbound and southbound decks are separated by a 5.5m gap over the full bridge length. A series of floor beams and inclined stay cables are utilized through the main span to transfer loads from the decks to the arch system. In addition, the main span has both lateral and longitudinal prestressed cables to increase the stiffness of the span and support the arch. Figure 2 outlines a typical cross section for both the arch span and non-arch spans.

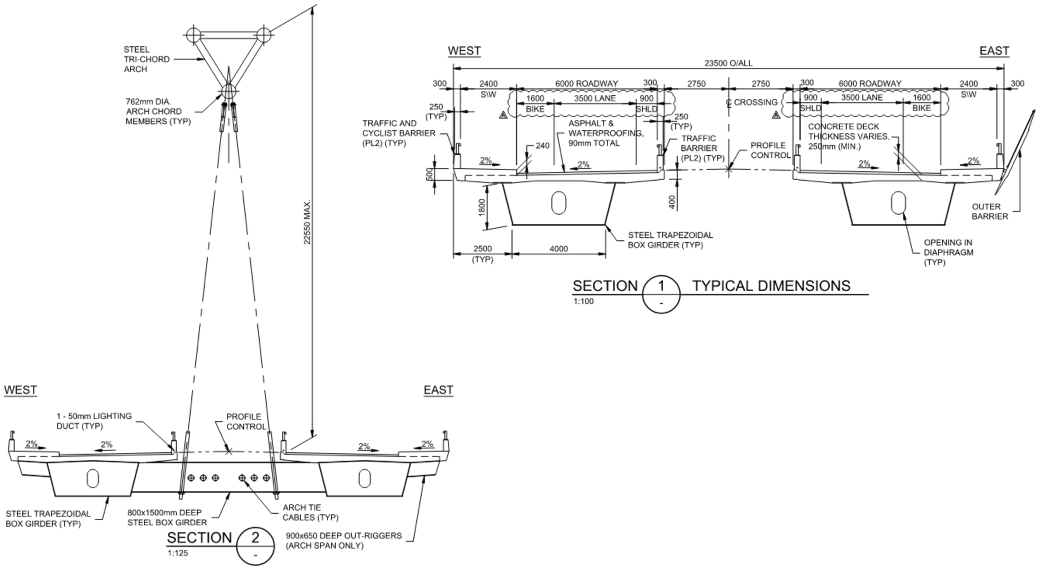

Figure 2 – Burgoyne Bridge Cross Sections

1.2 PROBLEM DESCRIPTION

Parsons was contracted by the Regional Municipality of Niagara (the “Region”) Public Works Department in 2018 to investigate means protection measures for the Burgoyne Bridge to prevent death from falling. While deaths by falling from the structure were reported on the original Burgoyne Bridge, there was concern that occurrences could increase due to the new landmark type structure. Parsons was responsible for investigating the feasibility of adding means protection barriers to the bridge based on solutions developed for other structures around Canada and world. Upon review of these case studies, a barrier system was designed to reduce the potential for deaths by falling from the structure.

Due to the geometry of the existing bridge, several forms of means protection could be adopted for the structure, namely vertical barriers or horizontal netting. The overall geometry of bridge and gap between the decks are shown in Figure 3. Since the bridge was constructed recently and involves unique architectural features, it was understood that the optimal solution would be one that minimizes the visual impacts to the structure while simultaneously simplifying construction through the incorporation of the existing bridge features. Due to the unique design and complexity of the existing traffic, pedestrian, and bicycle railing systems on the bridge, it was preferable to minimize the impacts to their design and functionality wherever possible.

Regardless of the chosen means protection methods, it is important to note that there is no solution which would fully remove the risk of deaths by falling from the Burgoyne Bridge. Even the most comprehensive and expensive systems installed at other bridges have had reported deaths since the implementation of means protection barriers. It is crucial that whenever similar barriers are installed on structures that client and the public are aware that with enough determination and manipulation, there is still a chance of deaths by falling from structures, even after the barrier is installed. The intension of the barrier is to provide sufficient deterrent to prevent such attempts.

Figure 3 – Burgoyne Bridge Exterior Edge (Left) and Interior Gap (Right)

1.3 MEANS PROTECTION

Means protection refers to the action of preventing or blocking the ability of a person to die by falling through various direct and indirect methods. Examples of means protection include barriers, nets, and the complete removal of pedestrian access. Such measures vary between encouraging a person contemplating death by falling to seek help, to physically removing the ability for such a person to fall. Deaths by falling from a bridge is a world-wide concern, with fatalities occurring at many landmark structures which become known as "magnets" for this type of activity. This means that once a structure becomes known as a magnet, falling contagion may result in an increasing number of deaths from the bridge. It is crucial that a system be put in place to prevent such notoriety and to remove the attraction of the bridge to persons contemplating death by falling (Toronto Public Health, 2018).

Generally, physical barriers are considered the most effective means of preventing deaths by falling as they restrict one's ability to make an attempt as well as provide a sense of imperviousness which may help to reduce the "ease" of dying by falling (Draper, 2017). Supplementary measures can also be installed in the form of signage, help phones, or security cameras, however these methods have only shown weak statistical evidence of effectiveness in reducing the rate of death, particularly if implemented on their own (Toronto Public Health, 2018).

When discussing deaths by falling from bridges, it is important to also consider the concepts of displacement and substitution. Displacement is the idea that a person contemplating falling who is blocked from dying at a certain bridge may look for other, nearby structures instead. Substitution is similar in concept, wherein a person may seek another method of dying by falling. Adding means protection barriers may reduce or eliminate the rate of deaths by falling at a specific bridge, but that does not guarantee that the overall deaths from falling from a height, or by any other means, will be reduced. Research has shown that at some locations there has been a partial counterbalancing at nearby bridges immediately following a barrier installation in which the deaths by falling increases at these bridges. This temporary displacement is then followed by a long-term stabilization and reduction in the overall death by falling rate in the area. Comparatively, research has indicated that at other locations there have been no signs of displacement or substitution after a means protection barrier was installed, therefore reducing the overall deaths by falling (Draper, 2017). However, the most important takeaway is that there is no guarantee that all deaths by falling from the Burgoyne Bridge, nearby bridges, or by any other means will be completely prevented after the implementation of a means protection barrier.

2.0 STATE OF PRACTICE

In recent years, much focus has been put on researching and understanding mental health issues and the reasons why a person would choose to die by falling from a tall structure. Combined with a push in refurbishing existing structures with means protection systems, and also incorporating such measures into the design of new bridges, many different means protection applications can be found. Specifically, means protection in the form of barriers has been shown to be the preferred method of preventing deaths by falling both in Canada and throughout the world. Few examples of netting systems on bridges exist and are only implemented when there are large concerns from the public regarding the aesthetic impacts of a traditional deck-mounted barrier. Many of these examples also have signs, security cameras, and help phones installed in addition to barriers.

Table 1 below highlights various different means protection barrier types used on bridges as well as the corresponding advantages and disadvantages of each barrier. These examples were closely studied for effectiveness, aesthetics, and construction feasibility while developing the design for the Burgoyne Bridge means protection systems.

Table 1 – Means Protection Examples

Structure	Description
Burrard Street Bridge Vancouver	Vertical painted steel pickets mounted on top of existing concrete parapet walls. (City of Vancouver, 2017) **Pros:** Ease of construction, simple design, minimizes visual obstructions, suits architecture of existing bridge, spiked pickets at top. **Cons:** Existing parapet wall provides standing point, horizontal members at top of barrier can be used as a lifting point, lacking a sense of imperviousness.
Ironworkers Memorial Bridge Vancouver	Vertical galvanized steel cantilevered pipe barrier acting as both a means protection barrier and a pedestrian and cyclist guardrail. (Saltman, 2017) **Pros:** Cantilever construction means no horizontal members near the top of the barrier, large diameter members resistant to bending, high sense of imperviousness, incorporates handrail system, tops of pipes cut at an angle to prevent being held. **Cons:** Large view obstruction due to larger picket diameter, imposing design doesn't suit bridge architecture, required removal of existing pedestrian railings.
Golden Gate Bridge San Francisco	Horizontal netting system supported by cantilever brackets installed 20 feet below the bridge extending 20 feet outwards. (Swan, 2018) **Pros:** Maintains architectural design of structure, no view obstruction from deck level, deters individuals from falling due to high likelihood of injury but not death. **Cons:** Very high installation cost, additional weight and wind load requires dampers to be installed and modifications to the bridge to reduce weight, individuals who do fall and are caught in the net would require rescue or may be able to fall further once they are on the netting.

Prince Edward Viaduct Toronto	5m tall vertical rods connected to an inclined structure supported off the side of the bridge. Barrier uses a system of cables to support the structure and reduce the impacts of additional wind loads. (McQuigge, 2017) **Pros:** Architecturally significant, extensive design with no hand or foot holds, thin vertical members reduce visual obstructions. **Cons:** High design and installation cost, reported death at the bridge even with the complex design, large size incurs maintenance access issues.
High Level Bridge Edmonton	Horizontal steel cable barrier supported by vertical posts mounted in front of existing pedestrian railing. (CBC News, 2017) **Pros:** Aesthetics match the bridge design, minimal cost for design and construction, no modifications to existing bridge, minimizes visual obstructions. **Cons:** Cost concerns took precedent over barrier effectiveness (only 50% reduction in attempts and deaths), horizontal cables can be easily climbed as a ladder, thin cables are susceptible to vandalism and have been cut on several occasions, tapered top interferes with cyclist headroom.

3.0 BARRIER DESIGN

3.1 DESIGN CONSTRAINTS

Upon review of the various options and systems available, it was concluded that a vertical barrier would be best suited on the exterior edges of the bridge decks, and to address the gap between the two decks, a horizontal mesh netting spanning the gap over the full length of the bridge would be preferred. As a starting point in the design process, the following criteria was developed for the successful implementation of a barrier on the exterior edges of the Burgoyne Bridge. This list was developed by analyzing past examples and guidelines (Toronto Public Health 2018).

1. A height greater than 2.5m above the sidewalk to prevent individuals from reaching up and easily pulling themselves over.
2. Gaps between components should be 150mm or less to prevent a person from passing through openings.
3. No foot or hand holds, particularly near the top of the barrier which would allow someone to lift or push themselves over. Likewise, any flat surfaces near the top of the barrier should be avoided.
4. The barrier should be comprised of smooth vertical components that are hard to grab onto.
5. The components at the top of the barrier (pickets, posts, pipes, etc.) should be angled or pointed to prevent them from becoming a hand hold.
6. A barrier should provide the impression of imperviousness. The more difficult a barrier looks to overcome, the lower the chances that someone will attempt to climb it. This can be done by increasing the height of the barrier, using solid and stiff components, and minimizing any hand and foot holds.
7. Structural and aerodynamic stability: any barrier system should not compromise the structural capacity of the bridge and should be sound under all conditions. Special consideration should be put into the wind and snow/ice effects of the barrier and the corresponding impacts to the entire bridge.

8. Accessibility should not be impacted by the barrier for vehicles, cyclists, or pedestrians.
9. Barrier aesthetics should match the existing bridge architecture as much as possible without sacrificing the means protection effectiveness.

Similar criteria were developed for the design of the horizontal net system for the interior gap between the bridge decks. The net system must be structurally sound, free of any openings that would allow someone to pass through and should give the impression of imperviousness.

3.2 EXTERIOR BARRIER

Design Considerations

The optimal exterior barrier design was required to meet several key points for effectiveness, appearance, constructability, and durability. Consideration was made for several different barrier options and materials and reviewed similar barrier types installed on other structures throughout the world. All barrier options were required to run continuously along all exterior edges of both decks for the full length of the bridge. Alternatives needed to minimize impacts to the existing pedestrian and bicycle railing systems which include architecturally significant aluminum components which would be difficult and costly to modify. The Region showed an interest in an angled barrier that would match the profile of an existing debris fence installed at the southeast end of the bridge and the angular facets of the parpaet walls. The outward angle of the barrier would help reduce the feeling of the barrier imposing on the bridge and would make it easier to minimize impacts to the existing railings. Additionally, a life cycle cost analysis was performed based on barriers constructed from either galvanized steel or aluminum (stainless steel was omitted due to the high material cost). The optimal material would be the one with the longest service life, lowest maintenance requirements and least life cycle costs.

Design Alternatives

Two alternatives were proposed for the exterior barrier based on the case studies examined. Both barrier options had the same inclined profile but had different vertical members which act as the primary means protection components. Picket style barriers were only considered, instead of mesh fencing, as mesh is not recommended for the purposes of a means protection barrier since it is easily scalable.

The first alternative was a cantilever hollow pipe design similar to the Ironworkers Memorial Bridge barrier. This type of barrier imposes a good sense of impassability, while the cantilevered pipe design limits the number of available handholds by not requiring an upper horizontal member for support. Likewise, the smooth surfaces of the pipes would prevent anyone from getting a solid grip and scaling the barrier. Many existing barriers of the same design can be found on landmark structures around North America, giving evidence of the effectiveness of this type of barrier. However, the view from the bridge deck would be more obstructed due to the large diameter pipes to allow for a cantilevered design. Damping of the cantilevered pipes is also required to reduce the effects of vibration as a result of wind, rain, snow, and ice loading. This issue is exacerbated when considering an aluminum barrier as it is much more susceptible to induced vibrations than steel, with vibrations starting at lower applied loads and lasting for longer durations. Finally, the lower stiffness of aluminum compared to steel would require even larger members to limit deflections of the pipes.

The second proposed alternative was an inclined supported picket barrier. Similar to the Burrard Street Bridge, this barrier type utilized solid round pickets supported with horizontal members at various heights. The benefits of this barrier type are the negligible dynamic considerations for the barrier as the pickets are fully secured at both ends and are not hollow. Additionally, the thinner vertical elements minimize the visual impacts of the barrier. The lighter components would also translate to reduced material costs as compared to the larger elements needed for cantilevered construction. However, the horizontal member required at the top of the barrier to support the upper portions of the pickets may be used as a handhold for a person to climb over the barrier. This barrier also has a much lower sense of imperviousness due to the thinner elements. As with the first option, this barrier could be constructed of either galvanized steel or aluminum.

A series of mockups were built during the design phase to evaluate the two alternatives for their means protection effectiveness and to refine the proposed designs. The mockups assisted with testing of both aluminum and galvanized steel sections to better understand and evaluate the deflection properties of each of the options and select appropriate member sizes for each barrier and material type.

Selected Design

The inclined cantilevered pipe barrier was determined to be the best option with regards to means protection. This barrier type provides a greater sense of impassibility, while the cantilevered design reduces the number of handholds making it very difficult to scale the barrier. The smooth, larger diameter pipes would be challenging to hold on to or use as a foothold, and the angle cut into the top of the pipes further limits the ability for an individual to attempt to climb over the barrier. Most importantly, there are numerous successful precedents that can be observed on several bridges throughout the world where the same barrier type has been constructed. While the second option may have been more cost effective and visually appealing, there were significant concerns regarding the means protection effectiveness as a result of the horizontal members near the top of the barrier.

Due to the lower service life of a galvanized steel barrier, an aluminum barrier was selected as a result of the severe environment that the barrier is exposed to, namely road salt and spray. Several connection plates, hollow structural sections, and pipes would be continuously exposed to these harsh conditions and would be difficult to maintain and clean, further reducing the service life of the steel option. There were also architectural concerns of using galvanized steel: as the galvanized coating erodes and the underlying steel corrodes, the appearance of the barrier would quickly degrade and tarnish the appearance of the structure as seen from the deck and the highway below. These concerns are greatly reduced with an aluminum barrier, however larger structural members are required to account for the reduced stiffness of aluminum as compared to steel.

The selected barrier utilizes 2” diameter cantilevered aluminum pipes acting as the primary means protection elements. The pipes have a clear spacing or 150mm or less and are supported by two rectangular aluminum sections running longitudinally and mounted to a series of I-section aluminum posts. The posts were connected to the bridge at every other existing railing post with a stainless-steel plate and bracket and were also anchored to the exterior face of the deck overhang. This allows the barrier to re-use the existing railing system anchor bolts and avoid having to add additional anchors into the parapet wall. To ease fabrication and construction, the barrier is constructed from panels ranging in lengths of 2 to 5 meters each. The east barrier is approximately 363m long and is comprised of 90 panels and extends onto a portion of the southeast retaining wall due to its tall height. The west barrier is approximately 314m long and is comprised of 78 modules. Finally, the ends of the barriers at the abutments have a 14” diameter stainless-steel tube to prevent a person from climbing around to the back of the barrier and traversing along it. Refer to Figure 4 for an installed picture of the barrier and typical cross sections.

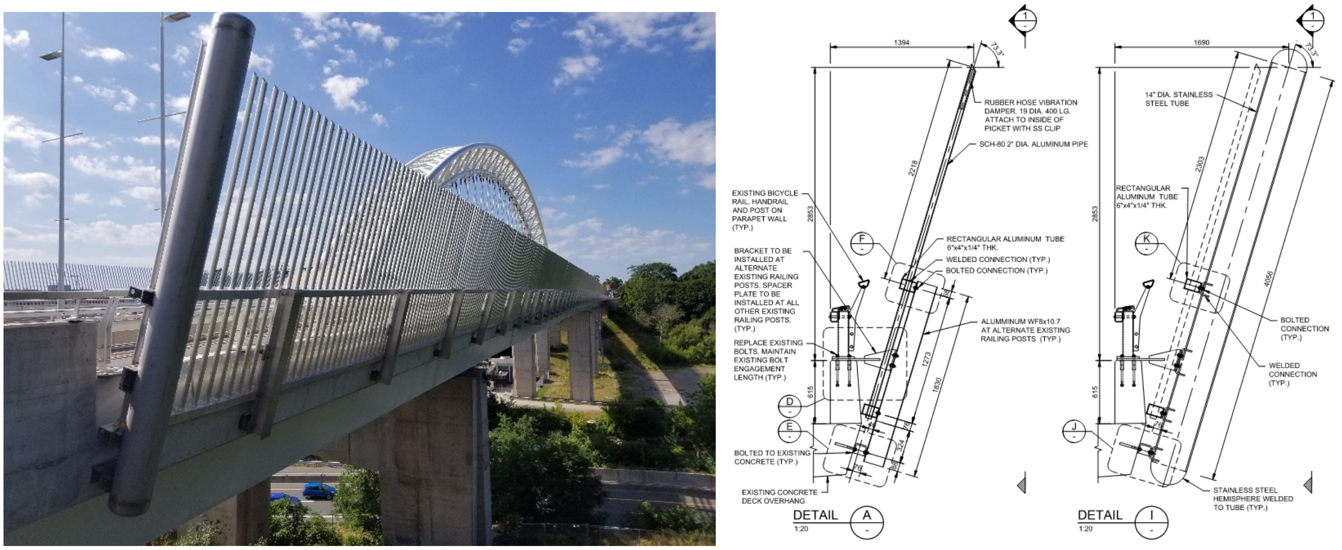

Figure 4 – Exterior Means Protection Barrier

3.3 INTERIOR BARRIER

Design Considerations

The selection of the means protection system along the interior edges of the bridge decks was a more straightforward decision than the outer cantilevered barrier. As with the exterior barrier, the optimal design was required to minimize impacts to the existing bridge railing systems and other bridge components. An additional constraint on the arch span is that the barrier cannot impact the performance of the arch hanger system. For these reasons, an inclined cantilevered pipe barrier like the one selected for the exterior edges was not possible as it would interfere with the arch and light posts.

After the elimination of a vertical barrier, the next logical step was a horizontal system which would span over the 5.5m gap between the parallel bridge decks. Due to the relatively close proximity of the bridge decks it was thought that the simplest solution would be to span a mesh fencing between the decks. Unlike a vertical barrier system, a net in this application would fully prevent an individual from bypassing the barrier in any way since all edges are bound by the existing structure. This alleviates the major concerns with other netting systems (such as the Golden Gate Bridge) in that there will be no option to bypass the net and fall further as it will completely fill the gap between the bridges. This system has been used successfully on several buildings where the ability to fall from the structure is fully removed by the net. A stainless-steel net system would be highly durable, weather resistant, and fully customizable to be able to fit the complex geometry of the Burgoyne Bridge.

Selected Design

The final design is a stainless-steel cable net running the full length of the gap between the bridge decks from the south abutment to the north abutment. The total length of the system is approximately 330m and is comprised of 82 modules of lengths of 3-5m each. The modules are supported by longitudinal cables adjacent to the bridge parapet walls and transverse cables at each module end. The support cables are connected to the bridge by stainless steel brackets which are bolted to the existing railing anchorages as done for the exterior barrier. The utilization of the existing railing anchor bolt assemblies for attaching the support brackets simplifies construction of the net and avoids time consuming anchoring into the existing concrete parapet wall. The stainless-steel netting and hardware will also help prolong the service life of the system which is exposed to severe environmental conditions. Refer to Figure 5 for a final installed picture of the net system as well as a standard plan section.

The barrier includes perforations in the net for the light posts, arch stay cables, and arch thrust blocks. The system uses a large mesh opening to discourage anyone from walking or climbing on top of the net. This will also reduce the visual and weight impacts of the system on the bridge and will limit ice, snow and debris buildup on the net. The system is mounted at the level of the existing railing base plates in order to utilize the railing anchor bolts. The benefit of this arrangement is that there would be no drop onto the net if someone attempts to climb onto it from the deck. The net would act purely as a fence system to block anyone from falling from the bridge, as opposed to a method of catching someone during a fall. Consideration was also made to mounting the net at the base of the parapet wall so that it would not be as visible from the deck level; however, there were concerns that if someone climbed down onto the net, they may not be able to get back out and would need to be rescued. It would also be more difficult to install and maintain the net system if it was anchored below the deck level. Finally, by mounting the net at the top of the parapets, the light pole pedestals and arch thrust block access panels are avoided, thereby limiting complicated mounting techniques and maintenance issues to the bridge and barrier during service.

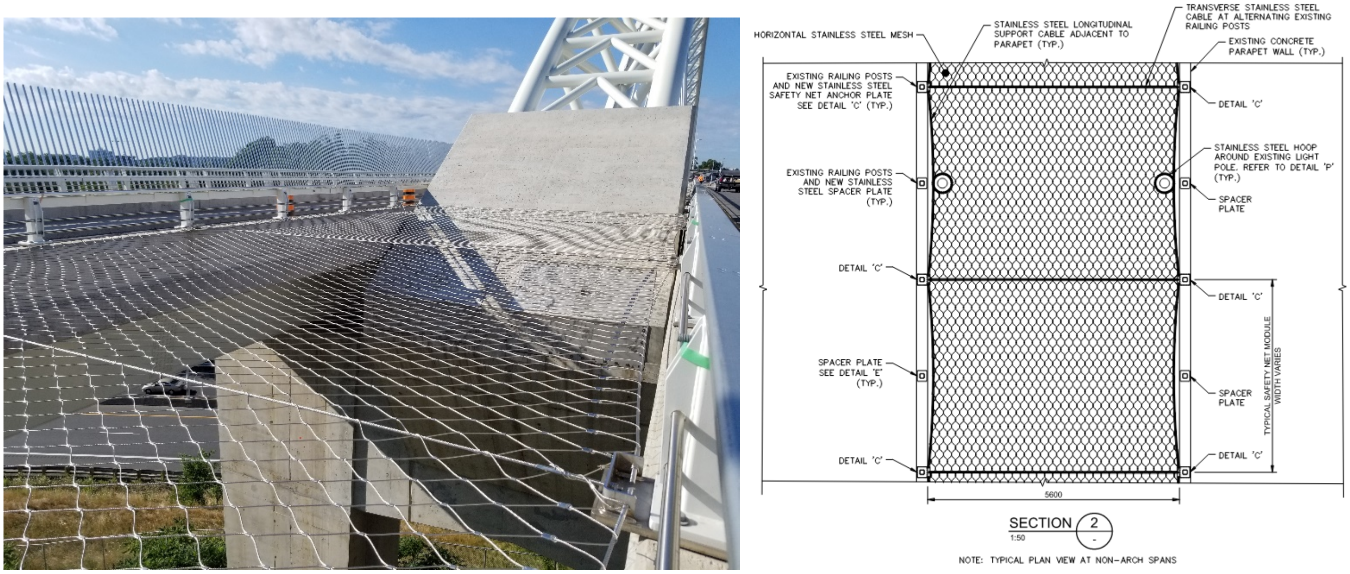

Figure 5 – Interior Means Protection Barrier

4.0 DYNAMIC ANALYSIS

Bridge Model

Parsons retained Rowan Williams Davies & Irwin Inc. (RWDI) to conduct dynamic analysis and wind tunnel testing of the proposed Burgoyne Bridge means protection barriers. RWDI constructed a scale sectional model of the bridge deck that replicates the main span geometry and mass distribution as shown in Figure 6. The model was tested in their wind tunnel for the wind speed range that was expected at the bridge. Tests were performed both with and without scaled models of the means protection barriers to assess the impact of the barriers on the overall aerodynamic stability of the bridge deck. Additional models of the barriers with assumed ice buildup were also tested. After completion of the tests, numerical methods were used to determine the wind loads acting on the structure and to ensure appropriate dynamic performance of the barriers and the bridge. It was determined that the bridge and the barriers performed adequately under all conditions.

Figure 6 – Bridge Scale Model Wind Tunnel Testing with Barriers

Material Selection

Parsons was also tasked by the Region to investigate the feasibility of both aluminum and galvanized steel for the construction of the exterior cantilevered pipe barrier. Due to the complex design of the proposed barriers and lack of any aluminum precedents, RWDI also assessed the dynamic properties of both materials to confirm whether or not they were feasible for this application. To assess each material, wind load results from the sectional model were used to compare the material and sectional characteristics of the two proposed options. It was determined that both material types were feasible from a dynamics perspective, however they would both require mass damping to eliminate vibrations of the cantilevered pipes induced by wind loading on the barrier. Due to the reduced stiffness and inherent damping properties of aluminum, a barrier with this material would potentially require more damping as compared to a similar steel barrier.

Barrier Damping

As aluminum has not been found to be used in any similar means protection barriers, more extensive testing was required to analyze and design an appropriate damping solution for the exterior barrier. As previously discussed, the cantilevered hollow pipes for the exterior barrier are highly susceptible to induced vibrations from wind loading. Mass dampers within each of the pipes were required to reduce vibrations caused by this wind loading and potential vortex shedding around the barrier components. Similar barriers using steel have also been shown to use mass dampers installed within the cantilevered pipes to dampen vibrations due to wind using minimal material and installation effort. It then follows that an aluminum barrier can use the same damping solution as these other examples, so long as the dampers are refined to suit the different material characteristics of aluminum as compared to steel.

To determine the vibrations, dynamic properties, and damping solution for the aluminum barrier, a full-scale mockup of one of the exterior barrier panels was prepared and tested as shown in Figure 7. It was important to investigate the performance of an entire panel as the vibration of the individual pipes can impart vibrations on the others as well, potentially affecting the level of damping required for the whole system.

Figure 7 – Panel Wind Tunnel Testing

Once the wind tunnel testing of the typical barrier panel was complete, the required damping for each hollow aluminum pipe was determined. As depicted in Figure 8, the dampers are primarily comprised of a 650mm long 19mm (¾”) straight PVC hose with a 13mm x 25mm stainless steel plug adhered to the low end. Each damper is bolted to the inside of each of the pipes at the top. This simple dampening system is able to dampen the vibrations of each of the pickets under all expected wind conditions once the barrier panels are installed.

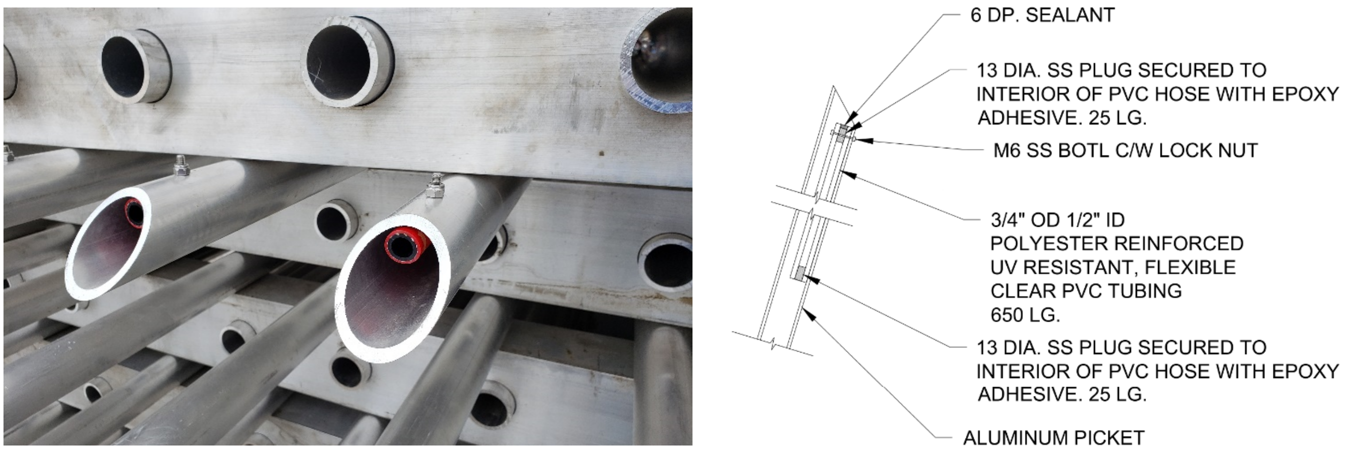

Figure 8 – Pipe Mass Dampers

5.0 CONSTRUCTION

Exterior Barrier

Prior to full production of the exterior barrier, a full-scale mockup of the exterior barrier was undertaken as pictured in Figure 9. The purpose of this mockup was to verify the construction techniques of the barrier and test the proposed damping solution. In addition, a test was undertaken to determine if the 150mm clear spacing between pickets was sufficient. During this test, it was demonstrated that a thin person could readily pass through a 150mm clear opening of the pickets, even when the pickets are retrained from prying forces. As a result, the design was revised to reduce the clear spacing between the pickets from 150mm to 125mm to eliminate the possibility of anyone being able to readily bypass the barrier. This is a very critical lesson learned for this project, as all previous reports stated that a clear spacing of only 150mm would be adequate to prevent all bypassing of the system.

Figure 9 – Mockup of Full-Scale Test Panel

The exterior barrier was designed in such a way that construction could be accommodated via lifting equipment situated on the bridge deck. The barrier brackets and posts were installed as a single piece by locally lifting the existing railing and installing a plate onto the anchor bolts holding the railing to the parapet wall. The lower portion of the posts were then anchored to the concrete deck fascia. Once the posts were installed, the vertical and horizontal barrier members were placed in prefabricated panels and bolted to the posts. This allowed for quicker construction as well as easier maintenance and replacement. If required, the height of the installed panels will allow a bridge master unit to reach over the top of the barrier for future maintenance and inspection of the bridge. The final material, delivery, and construction cost of the exterior barrier with mass dampers was approximately $2500 per meter length of barrier.

Interior Barrier

The interior mesh net was similarly installed from the deck level. The support cable brackets were installed between the parapet walls and railing posts by utilizing the existing post anchor bolts. Once the brackets were installed the longitudinal and transverse support cables were connected. The mesh net was then attached to these support cables. Localized openings were left in the mesh to allow the light poles and arch hangers to pass through without interference. The final material, delivery, and construction cost of the interior mesh barrier was approximately $350 per square meter. Significant cost savings were realized by utilizing the netting as opposed to vertical barriers to protect the gap between the bridges.

6.0 CONCLUSION

Based on research of means protection barriers installed on other structures throughout the world, two barrier types were selected based on their means protection effectiveness, appearance, constructability, durability, and maintenance. By utilizing cantilevered vertical members for the exterior barriers, the ability of a person to use hand holds to scale the barrier is removed, while providing a good sense of imperviousness which will help deter individuals from attempting to climb the barrier. The horizontal stainless-steel mesh net spanning between the two parallel bridge decks completely fills the gap between the decks ensuring there is no way for a person to easily fall from the bridge and proved to be a very cost-effective solution.

It is important to understand the wind induced effects on the bridge as well as the dynamic and vibration properties of the means protection barriers. Incorporating a full-scale mockup demonstrated value in validating the effectiveness of the barrier and allowed for an accurate wind analysis. Utilizing mass dampers in the vertical pickets was found to be an effective solution to prevent wind induced vibrations while also being cost effective.

While it is believed that the best possible solutions were chosen for this structure, it is worth noting that there is no perfect resolution to such a complex problem, and the installation of barriers does not guarantee that there will be no further deaths by falling from the structure. It is the hope of all who were involved that these barriers will help to save lives and protect the public for many years to come.

ACKNOWLEDGMENTS

Parsons wishes to acknowledge Region of Niagara Public Works Department for providing the opportunity to deliver such a unique and important project. Parsons would also like to thank the RWDI team for their expertise and support during the barrier preliminary design and wind tunnel testing.

REFERENCES

City of Vancouver. (2017, February 17). *City of Vancouver completes west side upgrades to Burrard Bridge* [Photograph]. Retrieved from https://www.kitsilano.ca/2017/02/17/city-of-vancouver-completes-west-side-upgrades-to-burrard-bridge/

Draper, J. (2017, January). *Suicide prevention on bridges: The national suicide prevention lifeline position*. National Suicide Prevention Lifeline.

McQuigge, M. (2017, June 20). Barrier at Bloor Street Viaduct significantly reduced suicides, study suggests. Retrieved from https://www.thestar.com/news/gta/2017/06/20/barrier-at-bloor-street-viaduct-significantly-reduced-suicides-study-suggests.html

Saltman, J. (2017, June 8). Metro Vancouver police chiefs call for suicide-prevention barriers on bridges. Retrieved from https://vancouversun.com/news/local-news/metro-vancouver-police-chiefs-call-for-suicide-prevention-barriers-on-bridges

CBC News. (2017, June 13). Suicide attempts on High Level Bridge down since barriers installed, city says. Retrieved from https://www.cbc.ca/news/canada/edmonton/suicide-attempts-on-high-level-bridge-down-since-barriers-installed-city-says-1.4158308

Swan, R. (2018, August 4). Golden Gate Bridge suicide barrier construction begins. Retrieved from https://www.sfchronicle.com/bayarea/article/Golden-Gate-Bridge-suicide-barrier-construction-13131352.php

Toronto Public Health. (2018, May). Interventions to prevent suicide from bridges: An evidence review and jurisdictional scan.