

PEACE BRIDGE DESIGN

INTRODUCTION

For the ESC101 Praxis design project, the Peace Bridge expansion and conflict was examined.

It is clear that the Peace Bridge, which spans over the Niagara River between the town of Fort Erie and the city of Buffalo, is in need of expansion and modernization. The Peace Bridge, which has served the area for 80 years, was designed before the great growth of automobile transportation in the 20th century (Lupfer, 1926). The Peace Bridge Authority, a governing body of 5 Americans and 5 Canadians, has examined plans of an expansion of the bridge (Chen, 1999). However, the Americans and the Canadians cannot agree upon a design to build. The Americans prefer a grand cable-stayed replacement bridge, while the Canadians would rather have a more economic “twin” built beside the existing bridge.

THE DESIGN

The goal of this design is to settle the two sides with a compromise between two ideals, worthy of the name “Peace Bridge”. The proposed bridge will act as a three lane companion bridge to the existing Peace Bridge, thus conserving a historical structure while constructing the necessary expansion for further use, as well as saving money on the demolition of the old Peace Bridge (as would have been required with an American cable-stayed replacement bridge design).

Daring Concrete Arches

In the proposed design, the main width of the Niagara River will be spanned by three thin concrete arches. From the

Canadian side to the American side, the three arches have span lengths of 150 m, 200 m, and 250 m, respectively. Each of the arches has a span-to-depth ratio of 10:1, maintaining visual unity.

The thin concrete arches are inspired by the works of both Robert Maillart and Christian Menn, two of the greatest concrete bridge designers of the 20th century (Billington, 1990). The particular thin arch design is mainly derived from the Infant Henrique Bridge over the River Douro in Porto. The designers of this bridge, António Adão da Fonseca and Francisco Millanes Mato, specifically quote Maillart and Menn respectively for their Schwandbach and Hinterrhine Bridges (Adão da Fonseca and Mato, 2005).

Indeed, the Schwandbach Bridge and the Infant Henrique Bridge are both deck-stiffened thin arch bridges, which is the type of arch chosen for the main Niagara River span of this proposed Peace Bridge design. The stiff deck of prestressed concrete works in conjunction with the flexible concrete arch to produce a system in which the completed bridge carries load, allowing for a much thinner arch than in more conventional designs (Billington, 1990).

Overhead Arch

Due to clearance requirements of the Black Rock Canal, a similar arch to cross the canal span was deemed impractical. Instead, an overhead concrete arch was chosen to cross the canal.

The overhead arch is to be constructed out of reinforced concrete, forming a true arch (rather than a tied arch), ‘suspending’ the roadway over the canal.

Inspiration and reference for the overhead arch came from a German bridge, Bridge over the River Saale by Winfried Glitsch (Glitsch, 2002). The overhead arch was chosen primarily for its elegance, which fits nicely visually with the

thin Maillart-style arches of the three main spans, and also for its easy integration with the box-girder roadway deck used for the rest of the bridge, thus reducing complexity and cost of construction.

Together, the overhead arch and the three concrete arches form the main portion of the proposed Peace Bridge expansion design. Aesthetically, the new design will create a contrast between the new and the old. Since the construction of the Peace Bridge 80 years ago, structural engineering has undergone many changes, especially in the use of concrete for bridges, pioneered by Robert Maillart. The thinner and longer span arches serve to complement the old Peace Bridge with a similar arched theme, while displaying with confidence the state of modern structural engineering.

COST

An advantage to this design over some other considered designs (such as a cable-stayed bridge) is the overall cost of construction. The Peace Bridge Expansion Project website lists the projected costs of several possible bridges for the project, and a concrete arched design similar to this proposal came in at a price range of \$95 - \$105 million, which is in fact the lowest of all the projected prices. In contrast, a cable stayed replacement bridge has an estimated cost of \$200 million, twice that of an arch companion bridge (Peace Bridge Expansion Project, 2006).

The low cost of the project should please the Canadians, who are looking for economic gains to the area from the project, while the elegant yet daring arches should also help bring the project more palatable for the Americans, who would like a grand landmark bridge to revitalize the city of Buffalo and the surrounding area (Chen, 1999).

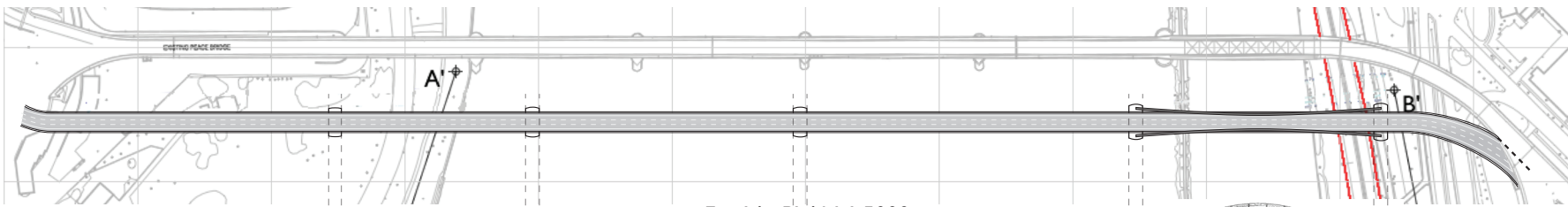


Fig. 1A- PLAN I:5000



Fig. 2B- Bridge over River Saale (Glitsch) Elevation I : 5000

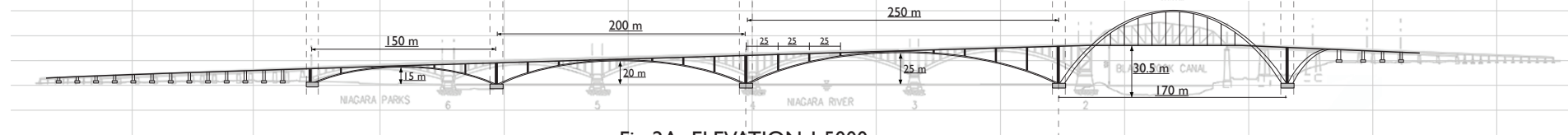


Fig. 2A- ELEVATION I:5000

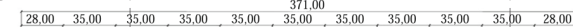


Fig. 2C- Infant Henrique Bridge (Fonseca, Mato) Elevation I : 5000

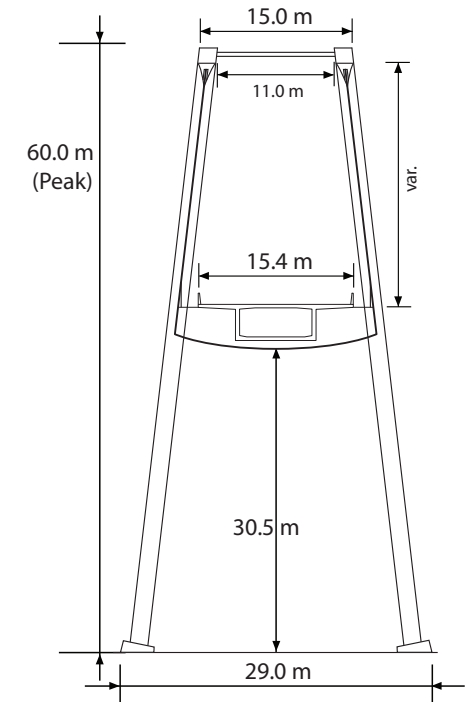


Fig. 4A- CROSS-SECTION I : 750

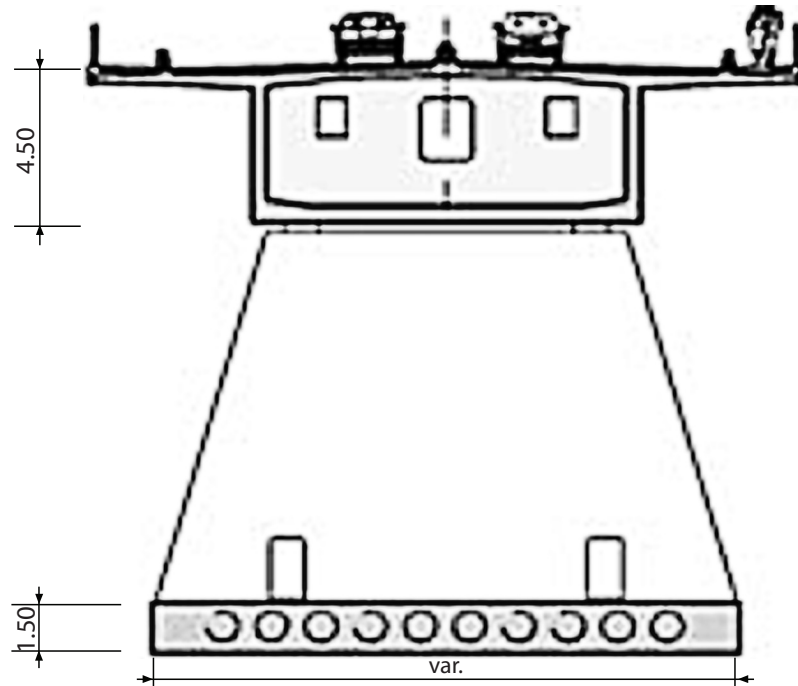


Fig. 3B- Infant Henrique Bridge (Fonseca, Mato) Cross Section I: 200

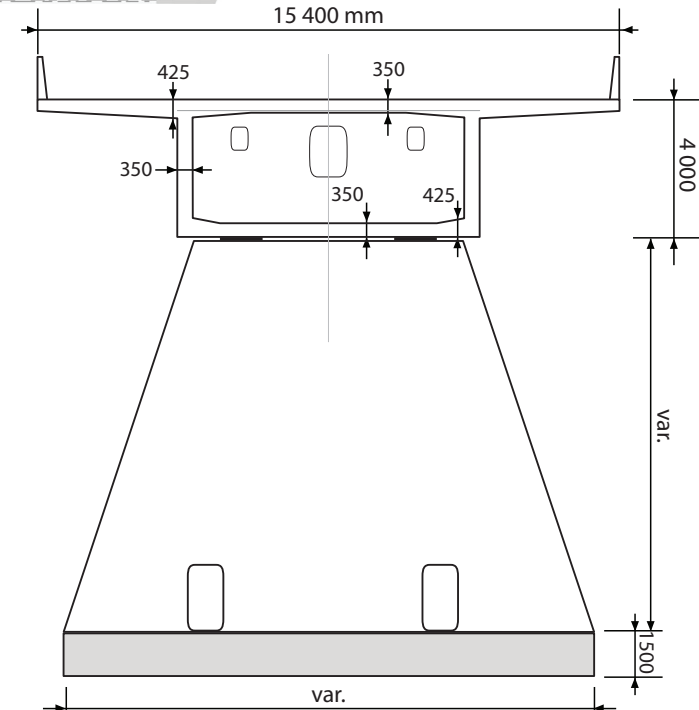


Fig. 3A- CROSS-SECTION I : 200

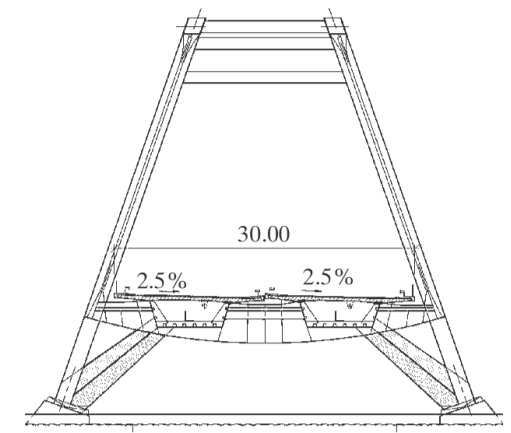


Fig. 4B- Bridge over River Saale (Glitsch) Cross Section I: 750

STRUCTURAL COMPONENTS

The primary design concept of the Peace Bridge expansion was to create a visually appealing yet cost-effective structural system for the Niagara River and Black Rock Canal crossing. Several systems were examined, such as a simple box-girder overpass (not unlike that of the Felsenau Bridge) and a larger cable stayed crossing. The chosen structural system was that of a deck-stiffened arch in conjunction with an overhead true arch.

Deck-Stiffened Arch

The goal of constructing a daring arch meant that a mere duplication of the five-span steel arch design of the existing Peace Bridge was too conservative. Since the original design of the bridge, there have been many advances in structural engineering.

The particular dimensions of the Niagara River crossing led to the decision to use three successively larger arches, each with a span-to-height ratio of 10:1. The arches are in essence three scaled models of the same arch. This enables the roadway to be elevated to a proper elevation to clear the Black Rock Canal, with a suitable gradient. The use of three arches that are identical but for its relative scale allows repetition of construction processes (since the arch sections will be pre-cast, as explained in the construction section), as well as simpler analysis of the structural system.

Each of the three arches over the Niagara Bridge consists of a thin and relatively flexible reinforced concrete arch, which acts in conjunction with a stiff prestressed concrete box-girder deck, hence the name “deck-stiffened arch” (Billington, 1990). The stiff arch acts as a beam on elastic supports, with columns spaced 25 m apart. It carries a significant percentage of vertically applied loads, and the percentage increases with asymmetrical live loads (Adão da

Fonseca and Mato, 2005), thus reducing high bending moments in the arch (this system was verified and used by the engineers who designed the Infant Henrique Bridge, which was a style pioneered by the works of Maillairt). This allows the use of a much thinner, flexible arch in place of a thick arch shape to counter bending moments, since the arch only needs to be thick enough to resist compressive forces rather than compressive and buckling forces.



Side view of the Infant Henrique Bridge, whose arch similarly varies in width from the base to the top. The Infant Henrique Bridge has a main arch span of 280 m, while the proposed arches will have a similar proportion, but a maximum span of 250 m.

The width of the arch decreases linearly as the arch approaches the center of the span, allowing for more cross-sectional area at the abutments to resist compressive forces produced at the abutments. Horizontal equilibrium of the arches at the abutments are maintained either by a second arch in the opposite direction, or by anchorage in the ground.

Overhead True Arch

The decision to use a true arch rather than a tied arch was to maintain visual unity where the arch met the foundation at the ground (rather than having a ‘floating’ tied arch), as well as to maintain a consistent box-girder cross-section throughout the bridge in order to reduce construction costs. The overhead true arch allows the same cross-section to be

used as the upward force from the arch will still be provided to the bottom of the girder using cables attached to a steel support structure, as shown in the cross section on page 2.

The angled pier on the east side of the overhead arch retains visual consistency, but is also a structural component which carries upward force from the ground to the support location at the bridge. However, due to its ‘diagonal’ alignment, it experiences a bending moment by the couple formed from the load of the bridge and the upward force from the ground. The bending moment is countered by thickening of the bottom of the pier relative to the top – as in the elevation view on page 2, the angled pier ‘thins out’ at the top as it approaches the roadway.

The angled pier and arch are a connected component, an idea similar to that used in the Bridge across the River Saale, where the angled piers and arch are structurally and visually connected to support the bridge.



View of the angled pier and arch connection at the Bridge across the River Saale. The pier and arch form a connected structural member which brings upward force from the ground to the roadway.

Further examinations of bridge loading are detailed on the opposite page.

SAMPLE LOAD PATH FOR DECK-STIFFENED ARCH

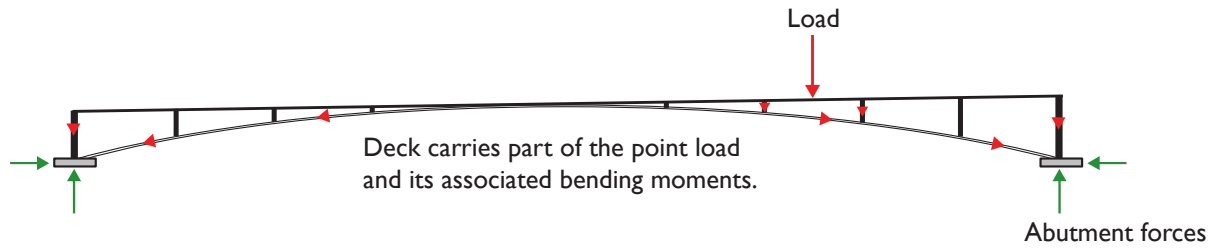


Fig. 5A- Elevation 1:2000

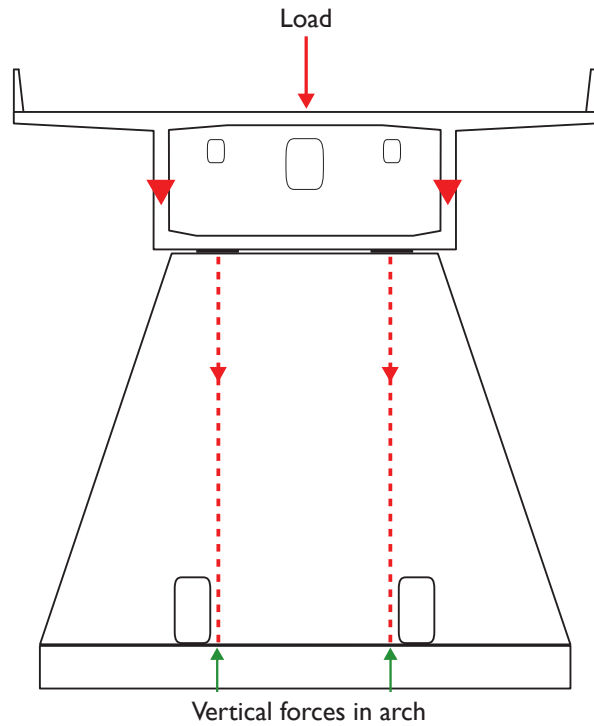


Fig. 5B- Cross-Section 1:200

SAMPLE LOAD PATH FOR OVERHEAD ARCH

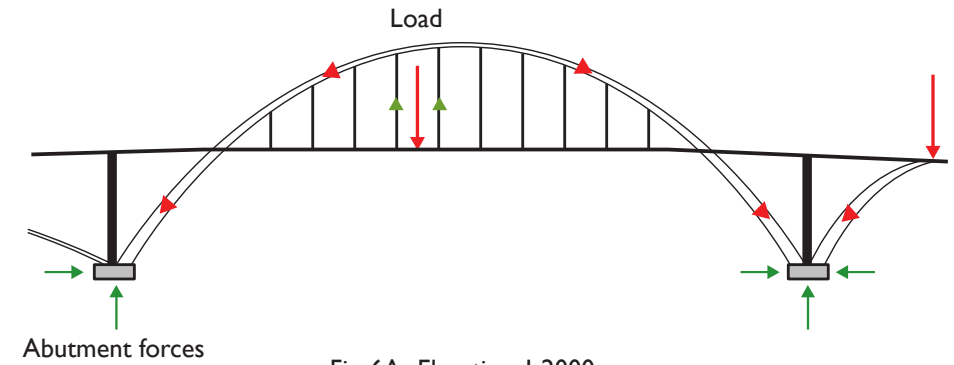


Fig. 6A- Elevation 1:2000

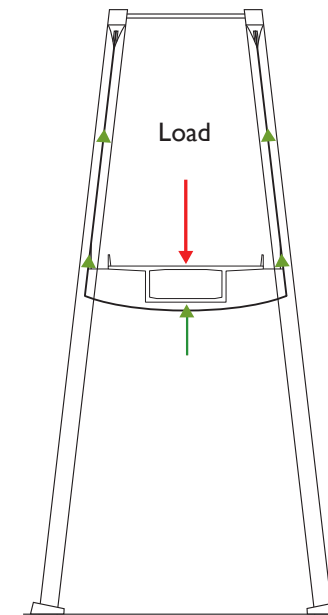


Fig. 6B- Cross-Section 1:750

Load carried by the steel support and cables, then transferred to the arches at the top. The arches then carry the load to the abutments and anchors as shown above.

AESTHETIC JUSTIFICATION OF BRIDGE COMPONENTS

DESIGN COMPONENTS

Angled Piers on the East End

On the east end of the bridge, at the American shore beyond the Black Rock Canal, a curved and angled pier was used to create visual unity with the overhead arch. Figure 7A and 7B show the contrast (in elevation view) of the completed bridge with and without the extra pier. It can be seen that without the curved pier, a straight pier would be required in its place to support the deck at that location. The vertical column does not have nearly the same elegance as the curved pier at the east end. With such an arrangement, the west and east sides of the overhead arch appear to be visually unbalanced. With the curvature of the pier, however, it does pose extra design complexities as the pier must resist bending moments caused by the separated vertical forces from the load and the support forces from the ground. It accomplishes this by using a wider cross-section at the base where it meets the ground.

Trapezoidal Piers Joining Deck and Arch

The arch and deck structure are joined by vertical piers, which have a rectangular cross section. The rectangular cross section is very slender and transparent when viewed from the elevation view, consistent with a thin arch which accomplishes the same visual goal of daring simplicity. The trapezoidal shape is required as the arch is wider than the box girder at the support locations. The decision to join the bottom edges of the trapezoid with the outer edges of the arch stems from the motivation of a thinly profiled arch. The

flush connection between the piers and arch thus serve to minimize the visual impact that the arch has on the eye.

At the top, it was decided that the girder and the column would not be built with flush edges. This decision is to create a visual separation between the deck and the arch structure. Since the deck is prominent structurally in its stiffness, this decision will give the deck an equivalent visual prominence, as its horizontal line will appear to be unbroken throughout the bridge. A comparison is shown in Figures 8A and 8B between a pier flush with the deck and a pier separated from the deck.

ARCH WIDTH

As shown in Figure 9A, which is a view of the bottom of the arch and deck structure, the arch is narrowed at the center where it meets the deck. The arch, at the point where it meets the deck, is narrower than the deck itself, which again provides the deck with an unbroken visual profile.

APPROACH PIERS

To have visual unity from a downstream or upstream view, the approach spans will have piers that are similarly profiled. A rectangular cross-section accomplishes this with minimal cost and construction impact. It will have the same thickness as the arch piers, and appear to be uniformly built.

VISUAL IMPACT

A primary motivation for the decision to use an arch design over a simple box-girder design was the aesthetic impact that a modern concrete arch would have.

Contrasting New and Old

First and foremost, the three thin arch spans plus the one overhead arch span contrasts greatly with the steel

structure of the old Peace Bridge. The concrete structure, with a daring 10:1 shallowness ratio and a thin arch with a thickness of less than 1/55 the span, represents a great deal of progress on the design and construction of bridges since the Peace Bridge was built, in the 1920s.

Arches are a very striking and symbolic element of the Peace Bridge design, and the consistent use of the arch form lends itself to a certain visual unity, even though the material and form of the arches are quite different. On the other hand, a cable stayed companion bridge or a box girder highway bridge would produce a glaring contrast that lacks any visual unity, making the Peace Bridge Expansion seem like an entirely separate project.

Transparency of Structure

The proposed bridge, consisting of relatively thin arches, has a very transparent profile. Viewed from downstream, the bridge does not obstruct the surrounding natural beauty of Niagara parks or the river, while deftly demonstrating modern engineering prowess. The transparent structure, using a minimum of materials, also allows the existing Peace Bridge, a historical monument, to be seen from downstream through the new bridge.

A New Landmark

While the Niagara River crossing is indeed a transparent, and almost minimalistic bridge that demonstrates structural art, a visual statement is also made with the unique overhead arch. The arches, which have a height of 60 m, can be seen distinctively over the flat landscape of the wide river. Such a unique shape provides the bridge with a unique character, which does not scream out for attention, yet is unmistakable in the landscape – an arrangement truly worthy of the name *Peace Bridge*.

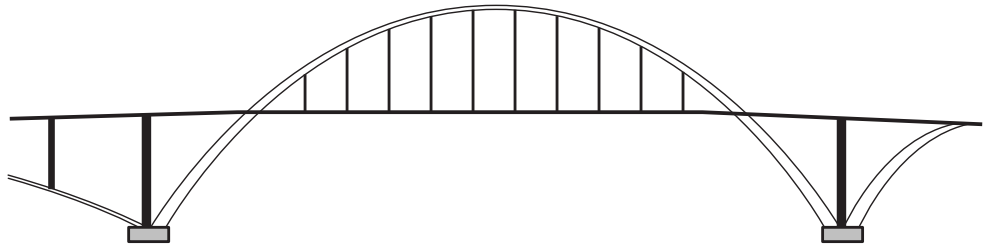


Fig. 7A- ELEVATION I : 2000

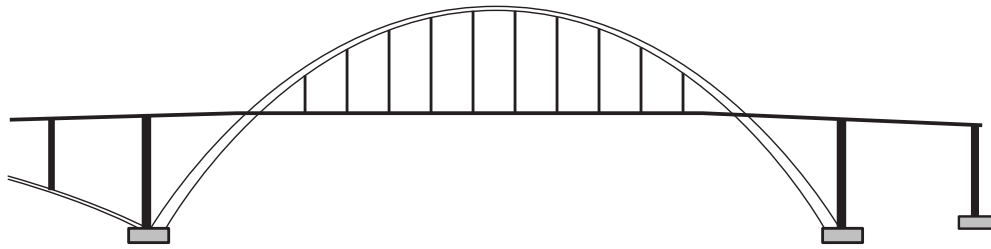


Fig. 7B- ELEVATION I : 2000

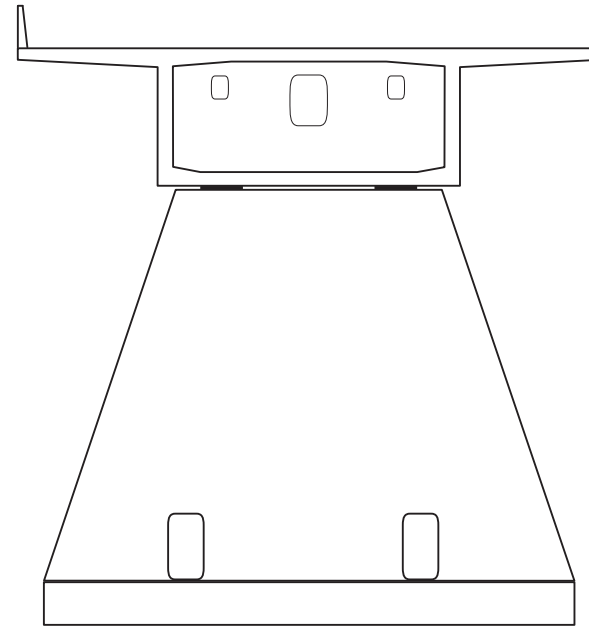


Fig. 8A- CROSS-SECTION I : 200

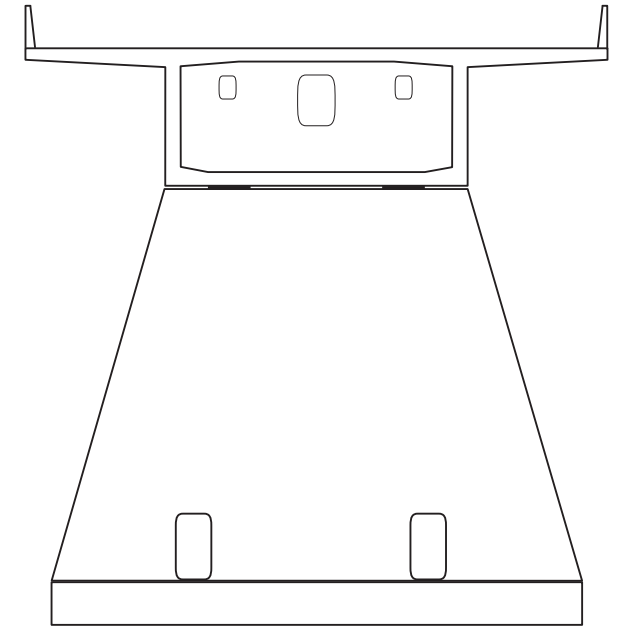


Fig. 8B- CROSS-SECTION I : 200

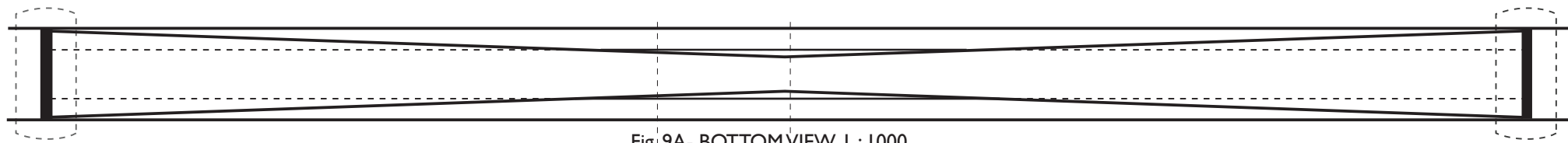


Fig. 9A- BOTTOMVIEW I : 1000

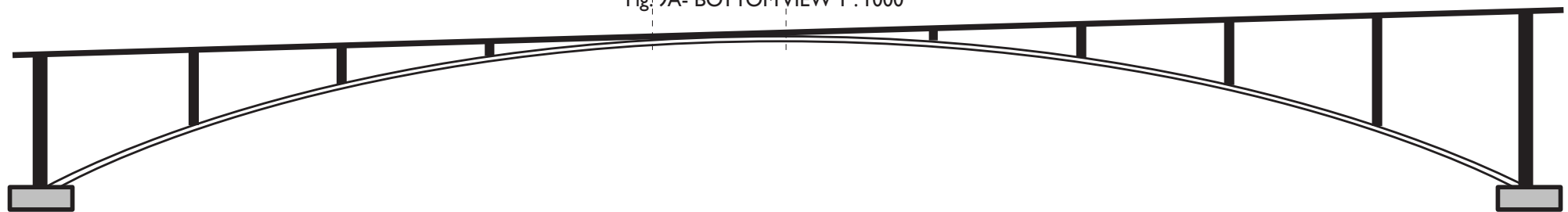


Fig. 9B- ELEVATION I : 1000

CONSTRUCTION

Approach Spans

The approach spans, which consist of simple concrete columns and a box girder deck, will be constructed first. The columns will be built into the ground, and temporary formwork is to be used, in order to cast the prestressed concrete box girder in place. The deck will continue to be advanced towards the river in such manner until it reaches the arches of the river.

Cantilevering

The structural functionality of a deck-stiffened arch bridge is dependent upon the arch member and the deck acting together. Thus, during the construction, it is not possible to treat the unfinished bridge as simply a part of the completed bridge. For example, a pure cantilever construction of the arches is not feasible since the arches do not function properly without the stiffened deck member.

The construction of the three main spans will require the use of temporary steel cables and struts, inserted between the arch and deck members during construction, which will essentially turn the uncompleted bridge into a truss. The bridge can then be built in a cantilever method. First, the main pillars will be erected upon an anchored concrete foundation in the Niagara River. Then, pre-cast sections of the concrete arch will be moved in and built on the pillar. Meanwhile, the box girder deck will be built on top of the pillar, and extended on both sides to maintain equilibrium.

Each pre-cast arch section will span the length from one supporting column to the next, which is a horizontal span of 25 m. The roadway-deck structure, which is to be cast in place using more traditional cantilevering methods with travelers, will be extended from each main pillar equally on

each side until it reaches the first 25 m, whereupon a pillar will be built to connect the arch and the deck. However, during the construction process, the incomplete arches are unable to sustain the load of the deck and pillars. Thus, steel cables will be connected at each 25 m pillar 'joint' diagonally from the arch to the roadway deck above at the next closest column from the pillar, forming a cantilever truss using the deck and arch as the top and bottom beams, while the columns serve as vertical members.

A similar approach was used in the construction of the Infant Henrique Bridge, using steel cables and struts to form a temporary truss with the incomplete arch and deck (Adão da Fonseca and Mato, 2005). This method of construction was deemed necessary as the use of falsework underneath the arches in the Niagara River would be uneconomical as well as prone to the dangers of the water current. In addition, while the Infant Henrique Bridge had used a temporary column in the construction of the arch, a similar technique would not be as cost-efficient in this case, as a temporary column must be placed into the Niagara River, meaning much more costly anchoring and casting is required underwater.

Temporary Towers

While the cantilever method ensured equilibrium by building out on both sides of the pillar equally, this is only applicable to two of the main pillars in the river, where two concrete arches meet. For the two ends, no equilibrium could be achieved with this method as the arch is only present on one side. In order to erect the pre-cast arch sections, temporary towers will be built to support the weight of the arch and deck structure during construction.

On the Canadian shore, the tower will hold up half of the smallest arch while it is being built. To maintain equilibrium

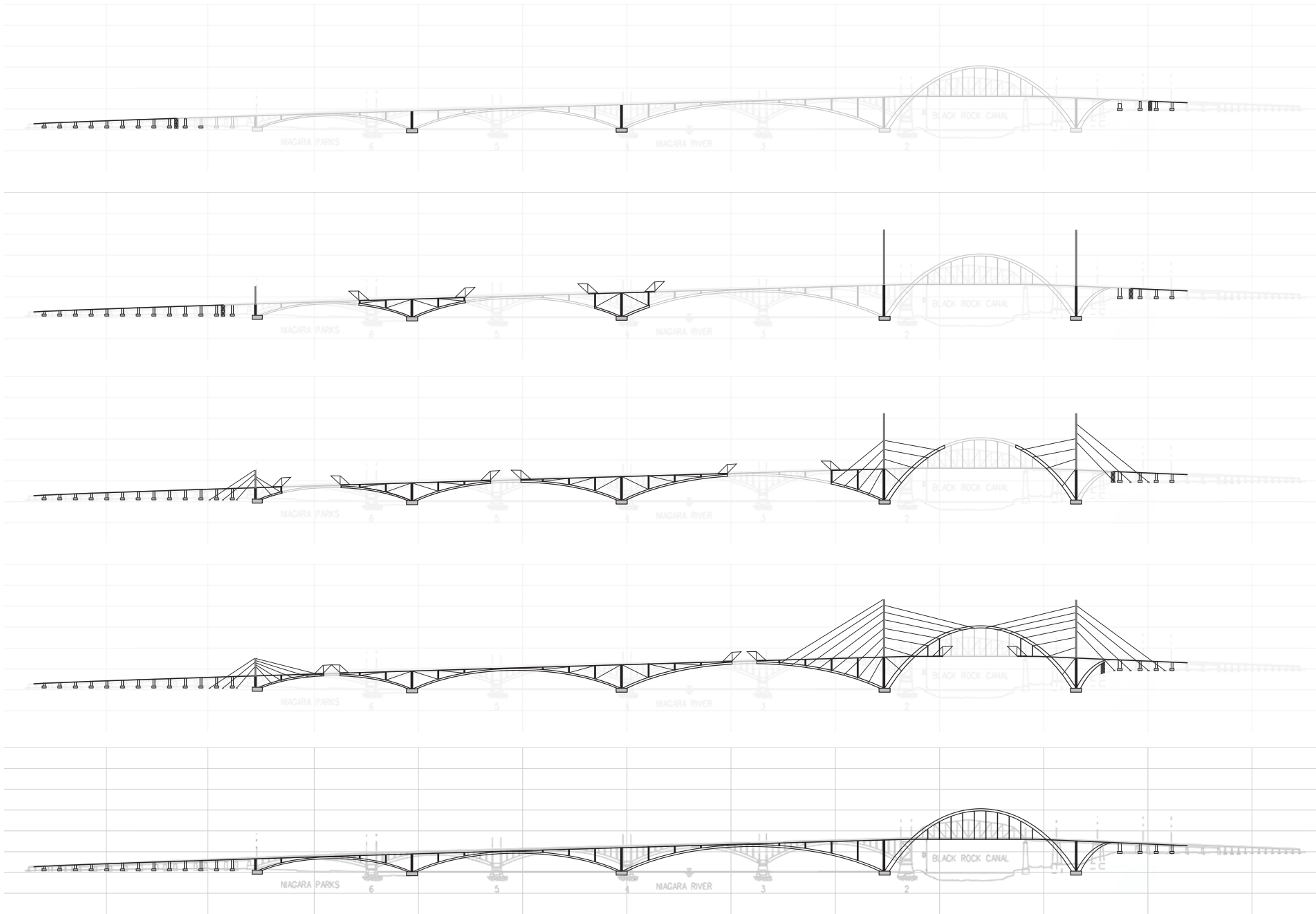
on the tower, the side of the tower not attached to the arch will be anchored to the ground using cable stays.

On the American side, where the overhead arch spans the Black Rock canal, care should be taken not to obstruct the canal during construction. The use of temporary towers and stays will allow the canal to remain open during the construction of the bridge.

Two towers, one on each side of the overhead arch, will be used to hold the reinforced concrete arch in place while it is being constructed. As with the thinner concrete arches over the Niagara River, the overhead arch will consist of pre-cast segments. The tower on the shore will be anchored to the ground by stays to maintain equilibrium, while the tower closest to the Niagara River will hold up the overhead arch on one side, and hold up the thin concrete arch closest to the Black Rock Canal on the other side, thus maintaining equilibrium between the two sides.

Once the overhead arch meets and is completed, the roadway will be extended from both sides of the arch, making the necessary connections to the arch (suspender cables to the overhead arch) until the roadway meets.

To complete the construction of the bridge, all temporary formwork for casting, the steel stays and struts used in the temporary truss structure, and the temporary towers will be dismantled and removed.



ELEVATION 1:5000

Piers are constructed in the Niagara River, while the piers for the approach spans are built one-by-one, and the deck is cast in place using temporary formwork.

From the piers in the river, the arch and deck structure are cantilevered outward while using temporary steel stays and struts to form a truss of the unfinished arch and deck. Meanwhile, three new piers at the overhead arch over the canal and the land pier on the Canadian shore are built with temporary towers on top.

Using the temporary towers on the three aforementioned piers, cable stays are used to hold the arch pieces in place while it is incomplete. Some stays are used to anchor the tower to the ground to maintain equilibrium during construction. The deck on the cantilever piers are continued outward at the same time.

The cantilever spans are extended until it meets the other side and the arch, then the travellers are removed once the arch is 'complete'. The towers and cable stays continue to be used to hold up the incomplete arches as shown until they meet at the center. When the overhead arch is completed, the roadway is extended from both sides.

To complete the construction, the temporary formwork, towers, cable stays, steel struts and stays in the cantilever truss structure are removed.

SUMMARY

The Peace Bridge is in need of expansion due to increased traffic in recent years. Due to a conflict of ideals between the American and Canadian interests, a stalemate has been reached and construction plans on a new bridge have been halted. (Chen, 1999).

This proposal aims to provide a compromise between the two ideals, one of economic gain and the other of visual grandeur. Using modern technology, the proposal aims to produce a bridge over the Niagara River and Black Rock Canal consisting of three deck-stiffened arches and an overhead arch. This combination provides both visual impact with its daring slenderness and shallowness, while keeping unnecessary costs to a minimum.

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