DESIGN AND CONSTRUCTION OF THE CAPILANO CLIFFWALK BRIDGES

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BIOGRAPHY

Kent LaRose has over 16 years of engineering and surveying experience with bridge engineering and physical infrastructure associated with highways, including managing international work. His study of shear stud clusters for full depth precast concrete deck panels is researched in the recent revisions of the Canadian Highway Bridge Design Code issued in 2010.

Scott Loptson has specialized in bridge & structural engineering for the past 15 years, including conceptual & detailed design, inspection, load ratings, rehabilitation, & construction projects. His responsibilities also include contract preparation & administration, cost estimates, & specification preparation.

Ruby Kwan is a bridge engineer in training in with both conventional and design-build experience. Ruby brings with her a diverse background in the timber, steel and concrete bridge design, field services, and contract administration.

Stuart Masterman is a transportation engineer in training with significant field experience in a range of civil projects throughout Western Canada. Stuart brings with him a background of engineering survey experience and environmental engineering training.

All four engineers are employed by Morrison Hershfield Limited, an employee owned company with offices across the United States and Canada.

SUMMARY

Cliffwalk is a thrilling attraction that is 30 stories above the river at its highest point at the Capilano Canyon. The unique pedestrian steel walkway is 1.64 ft wide and is cantilevered approximately 10 ft from the cliff face. It is 700 ft long in total and is said to be first of its kind in the world.

Fabrication and erection techniques for the project have been described as "leading-edge" by the steel fabricator. Also of note is the iterative combination of survey/design/fabricate/erect used to construct the steel walkway.

Site accessibility was extremely limited and the steel members were originally designed so that construction of the structure can be done using minimal manpower. Only a small crane was required during the erection of the curved bridge and a few long bridge segments.

The critical success of the Cliffwalk is that the entire structure was constructed by impacting only 118 ft^2 of foundation area, including avoiding key areas of the rock face that is covered in grass, moss or ferns.

Cliffwalk was designed in conjunction with the David Suzuki Foundation. The structure also serves as the medium to tell the story of the water cycle and its importance to life.

DESIGN AND CONSTRUCTION OF THE CAPILANO CLIFFWALK

1.0 Introduction

Surrounded by temperate west coast rainforest just minutes from downtown Vancouver, the Capilano River attracts hundreds of thousands of visitors to the Capilano Suspension Bridge Park all year round. In 2007, after rappelling down the east face of the Capilano Canyon, John Stibbard, Vice President of Operations for Capilano Suspension Bridge Park, found an ideal location to create a new thrill for park visitors in addition to the existing 450 ft long famous suspension bridge and the Treetop Adventures. However, having over 750,000 annual guests to enjoy the beautiful West Coast rainforest canyon by using standard rock climbing techniques would not be feasible because it would destroy the natural flora/fauna on the rock face and would create safety and liability concerns for that many people. All of this presented the challenge of how can they safely provide guest access to the cliff face while having minimal impacts to the environment?

Besides being a new thrilling attraction in the park, Cliffwalk also serves as an educational tour by partnering with the David Suzuki Foundation, which is a non-profit organization that works with government and businesses to conserve the environment by providing science-based education, advocacy and policy work. Educational panels with ecological information along the Cliffwalk pathway provide guests with information about the natural water cycle, characteristics and formation of the canyon, aquatic life, and natural vegetation, which can be seen down to the river below.

The Cliffwalk pedestrian structure is the product of years of innovative design and planning, and had many difficulties to overcome as the project progressed. One of the first was how to obtain a building permit for such a unique structure from the District of North Vancouver. Another was how to mitigate rock fall hazards and provide visitors with a safe structure that would be slender, light and airy, and as thrilling as the other structures in the park? What alignment on the cliff face should the Cliffwalk take and how would the structure be built in a rainforest with minimal environmental impact and extremely limited construction access? These are only some of the many engineering challenges that needed to be resolved during the course of the project.

The unique nature of the steel structure required an iterative combination of survey, design, fabrication, and erection methods. For example: the cliff face had to be surveyed to determine the pathway alignment by establishing suitable anchor locations; next, the proposed anchor locations were surveyed in detail to design the anchors; rock anchors were then installed into the predetermined locations and their positions surveyed and updated in the 3D structural detailing model to finalize the geometry. This iterative process and the unique nature of fabricating and erecting the steel on the cliff face are considered to be the first of its kind in the world.

1.1 What is Cliffwalk?

Cliffwalk is located in the Capilano Suspension Bridge Park with the main attraction at the park being the 450 ft long, 230 ft high suspension bridge over the Capilano River which was first built in 1889. The Treetops Adventure, which was completed in 2006 on the west side of the park, also increased visitors' experience by providing access to the canopy of the rainforest. The park offers a number of educational opportunities for its visitors which are unique to the west coast such as First Nations culture, local history, aquatic and terrestrial life, flora/fauna of the rainforest and the rainforest canopy. Unique infrastructures

were constructed to provide access for each of these while conserving the natural environment of the park.

Cliffwalk is a pedestrian walkway, which at its highest point, is 30 stories above the Capilano River. It travels along the granite cliff on the east face of the Capilano Canyon. The 700 ft long steel structure is 1.64 ft wide and is cantilevered approximately 10 ft out from the cliff face. The structure brings visitors down along the cliff by a spiral stairway; 8 bridge spans; 5 straight stairways; 7 observation platforms (two with glass decks); and a 100 ft long cable supported semi-circular bridge; and it provides countless thrilling experiences (See Figure 1).

Figure 1. Cliffwalk general view.

The project has allowed the owner of the park to reclaim over 2 acres of land into usable park space by terraforming an old gravel landing and installing a new walkway and landscaping. One of the significant successes of the Cliffwalk is that the 700 ft long steel structure was constructed by only impacting 118 ft^2 of rock face area for the foundation supports while avoiding key areas of the rock face that is covered by grass, moss or ferns.

2.0 Data Gathering and Permit Application

Prior to doing any construction on the Cliffwalk, a building permit was required from the District of North Vancouver. However, the permit application requires a number of reports and surveys of the site including a topographic and cadastral survey which is the base of the application design drawings, an environmental report, input from the landscape architect, a tree survey by a professional arborist and a geotechnical report.

Accessing the cliff face and the sloped ground at the canyon was a challenge for the project. Survey crews gained access by using ladders, ropes and advanced vertical lifeline techniques for this unusual setting. The challenge was overcome with a combination of good planning, experience, training and patience.

Typically, rock face surveys are undertaken using an automated scanner which is set up in a stable location with clear sightlines to the cliff. This technique allows fast, efficient data acquisition over a large area. However, the proposed Cliffwalk alignment and surrounding cliff face is mostly obscured by the dense coastal rainforest vegetation which made using this technique impossible. Instead, a topographic survey using a total station was conducted with the main challenges being access and clear sightlines to the cliff face. Due to the huge logistical challenges of this survey, average survey field production rates were cut by a factor of approximately five to ten when compared to a 'typical' topographic survey of comparable size.

Topographic surveys mapped the features of the cliff face including any ledges, overhangs, trees, gullies, major cracks or caves that should be noted for accommodation during the design. The survey mapped additional features such as the park's existing wooden deck and the foundations of the existing building at the top of the cliff. In addition, a full ground profile was surveyed from the base of the cliff down to the Capilano River at the canyon bottom.

For ease of access, lightweight equipment was required for surveying along the face of the cliff. A Leica TCRA 1103 total station was selected for its relatively low weight within its class of instrument, and customized survey legs were built for setting up the instrument on very high angled ground (See Figure 2). A majority of the survey data was collected using the reflectorless capability of the total station; however, it was not always possible to have direct sightlines to all features on the cliff. At these instances, a surveyor would rappel down the cliff face with a target reflector to gather additional data that could not be seen directly from the ground.

Figure 2. Typical topographic survey along the cliff face.

The initial survey was the first of many iterative surveys throughout the project. As the walkway alignment was further developed, more detailed data was collected around foundation locations, anchor points for cantilevers, tree locations etc. Survey brackets were mounted onto the rock face at critical locations such as the rock anchors for the curved bridge. These allowed high density survey data to be collected for design and also allowed high accuracy layout to be conducted at these important sites during the construction stage.

Due to the complex geometry of the cliff face, conventional drafting techniques for producing a 3D digital terrain model (DTM) could not be used. Overhangs present a problem in the software used to create the common DTM, therefore an innovative drafting technique was devised to overcome this problem. Individual 3D faces were manually created from the survey points gathered to establish a 3D model of the entire cliff face. This required close communication and constant quality control checks between the field staff and the drafting personnel. Drafting in this way is a complicated process that requires excellent 3D visualization skills and the resulting 3D model was used effectively by the engineering team to design the Cliffwalk (See Figure 3).

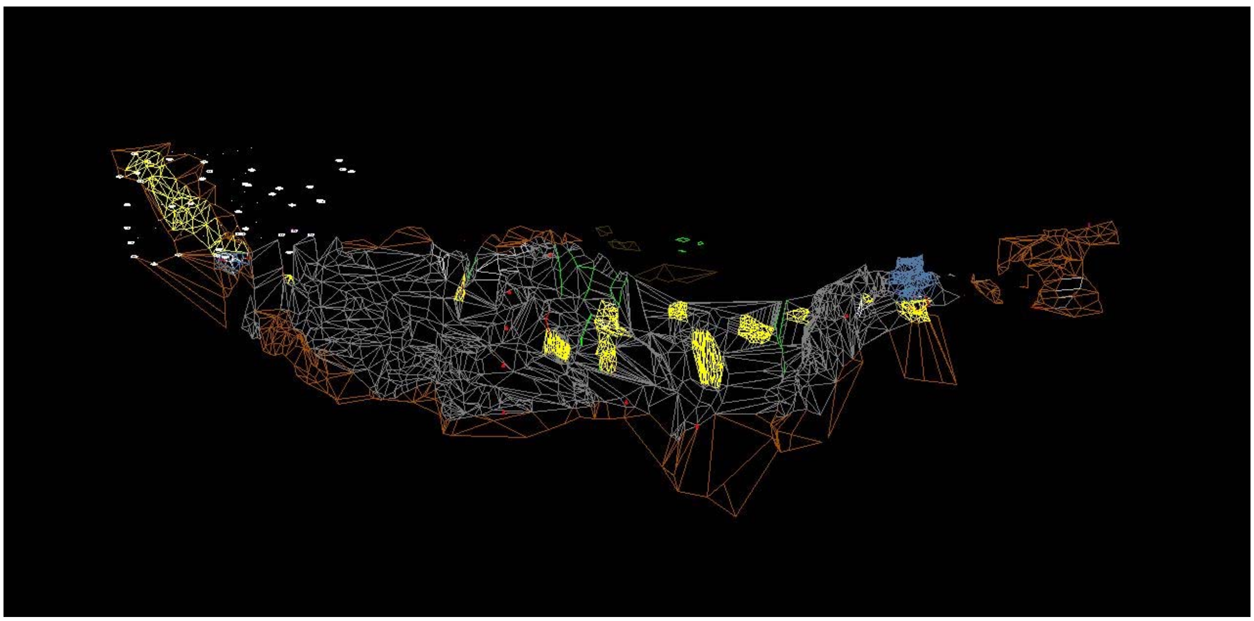

Figure 3. 3D model of the cliff face.

Besides using surveying equipment, the cliff face was also studied by rock and structural engineers using high angle rope techniques and rappelling to establish the walkway alignment by finding suitable foundation locations and areas that required rock stabilization. This was done every 10 to 20 ft along the length of the cliff face above the canyon to map and evaluate the rock. It was found that the rock throughout the canyon is very strong and massive 160 million year old granite. It took months of work to survey and map out the cliff face in order to produce enough useful information to complete the design of the Cliffwalk.

3.0 Design Development

The design criteria for the Cliffwalk was to satisfy all limit states to achieve the objectives of constructability, safety, and serviceability with primary concern being the safety of the public, including during construction and maintenance. The design was based on Canadian Highway Bridge Design Code (CAN/CSA-S6-06) and National Building Code of Canada 2005 (NBCC). It was determined that for the design of this special structure, it was most appropriate to treat the structure as a pedestrian bridge using the bridge code, CAN/CSA-S6-06. Additional guidance was taken from the American Association of State Highway and Transportation Officials (AASHTO), American Institute of Steel Construction (AISC), and further technical literature where none is provided by either code.

The owner's intent of the design was to provide a "lively" structure by targeting fundamental frequencies that are considered close to uncomfortable for human use to add onto visitors' excitement. Slight vibration can be felt along the walkway especially at the curved bridge which is supported by 9 cables and cantilevered out from the cliff face some 50 ft at its farthest point. There is also a possibility for "vandal" excitations where individuals would attempt to deliberately excite the structure by actions such as jumping in unison. The whole Cliffwalk as well as the rest of the park are monitored with numerous CCTV cameras where staff are present to supervise the use of the structure.

At the early stages of project, it was found that a significant amount of collaborations were needed between the owner, rock engineer, structural engineer, surveyor and erector since the design, fabrication and construction techniques were all going to be heavily interconnected and interdependent. Significant back and forth communication during the design development was required to determine anchor points and foundation locations.

In total, 12 different alignment designs of the Cliffwalk were considered before arriving at the final design. The initial alignment's design required almost 20 stories of vertical difference in elevation since it went from the top of the cliff down to its base near the Capilano River, but the amount of stairs needed would have been too overwhelming for the average visitor. The rock fall hazard would also be higher for the alignment being at the lower point of the cliff due to the exposure of a larger rock face area above the walkway. Some alignment configurations were also discounted because of poor conditions of the rock at anchor locations or foundations that were only determined once a preliminary alignment was developed and then surveyed on to the cliff face. The entrance of the Cliffwalk was originally located just beside the entrance of the main suspension bridge; however, the owner of the park thought this would create congestion of visitors and desired to passively distribute visitors into different areas of the park.

The final design consists of a descent of 29 ft (3 stories) down from the entrance of the Cliffwalk to the curved bridge, and then an ascent of about 58 ft (6 stories) back to the trail system at the exit of the structure (See Figure 4).

Figure 4. Ascending stairs.

Once the alignment was finalized, additional topographic survey was needed for collecting more detailed information of the locations of interest. This survey would provide accurate data to be used for the design of the steel structure as well as foundations and landscaping areas. Custom built anchor brackets were mounted on the rock face at the anticipated anchor locations to allow for a surveyed fitting on the uneven rock face and to provide a clear location in some hard to see areas.

Once the final locations of the anchor plates were established, 3D lines were created in AutoCAD to model the steel anchors that would be attached to the rock face. These lines were projected in the field and marked at the intersection of the model with the rock face by the surveyors. This was a critical step since the directional accuracy of the rock bolts and steelwork was a key element in the design of the walkway.

3.1 Rock Engineering

Rock engineering was an important part of the Cliffwalk design. The primary issues were to determine the location of stable anchorages for each of the foundations and to assess and mitigate the stability of the rock face. To decrease the probability of potential rock falls, the structure was placed high on the canyon wall to limit the cliff face area above the structure that would be a source of rock falls. In addition, by having the Cliffwalk located a minimum of 10 ft from the vertical cliff face, a majority of the rocks would be expected to fall close to the face (between the structure and the cliff face) and not bounce out onto the walkway.

The geotechnical investigation involved rappelling down the cliff face over the full length of the alignment to map the rock and locate geological features such as faults, open tension cracks and areas of fractured rock. Depending on what feature it was, appropriate remedial measures were done such as moving the foundation to a more stable location, or stabilizing the rock by a combination of hand scaling to remove loose blocks of rock and installing rock bolts (See Figure 5). In some instances, the remedial measures were not determined until the rock drilling was underway, requiring structural solutions to be designed while components were already being fabricated.

Figure 5. Typical rock bolting construction.

The rock bolts are all galvanized steel bars, either 1” or 1¼” in diameter and up to 18 ft long, depending on the rock conditions and the loads applied by the structure. The bolts are anchored with cement grout over the full length of the bar so that the combination of galvanizing and embedment in cement provides corrosion protection for the steel. The total length of rock bolts installed on the project for both rock reinforcement and securing the foundations is approximately 1673 ft.

The District of North Vancouver Noise Regulation Bylaw was followed for the rock drilling, ensuring that the construction operations did not emit a continuous sound level that exceeds 80 decibels when measured at the point of reception. In this case, the closest point of reception was at the lookout deck on the top of the cliff above the curved bridge which is 100 ft from the noise generating spot. The largest source of noise was caused by rock drilling with pneumatic equipment and it was required that this equipment be muffled and that drilling operations be limited to only daytime hours. Other special measures included that the rock drilling equipment was to be covered to contain the rock dust created from the drilling and that the dust was to be captured and disposed at a suitable location.

Access to the cliff face was relatively simple for basic workers with their light equipment. It was accomplished with rappelling equipment and static lines. The heavier drilling equipment and construction materials complicated the access, particularly for the rock stability work prior to the start of construction. The rappelling equipment was planned and arranged to avoid areas with flora and fauna that needed to be preserved.

At each foundation location, rock bolts were installed to support the applied loads – either tension at the guy cables or compression at the cantilever beams. The design load of each bolt is 50% of the ultimate strength of the bolt, which is a standard practice. The installation procedure was to first install the bolts and conduct pull tests to verify the capacity of the grout anchorages. The testing of rock bolts was done as per the Post Tensioning Institute. Then the anchor plate was attached to the face and the bolts were tensioned against the plate. The objective of post tensioning the bolts was to prevent any movement of the foundation once the bridge load was applied. The steel framework was installed as the foundations and rock bolts were established.

3.2 Structural Engineering

Different structural forms for the cliff face structure were investigated including suspension bridges and suspension supported stair cases which would match the other existing suspension structures in the park. Using timber as structural members was discounted because of durability requirements insisted on by the owner. The use of concrete structural members was also deemed not feasible due to the construction nature of the material as discussed with the contractor and the environmental concerns such as spills of concrete into the river. Galvanized steel was determined to be the superior choice for cleaner aesthetics as compared to competing materials and provides the required durability.

A steel framework was decided as the optimum choice for this special terrain. In addition, for sustainability, steel is the most recycled material in North America and has the highest overall recycling rate of any material on the planet according to AISC. The Cliffwalk consists of approximately 80,779 pounds of steel in total.

The final arrangement of the structure is a combination of steel frames with mostly propped cantilever supports from the cliff face. Each of the propped cantilever supports have two tension ties to provide a measure of redundancy in the load path, which is considered as one of the redundancy classifications described in the National Steel Bridge Alliance (NSBA) Steel Bridge Design Handbook. There are also a few pure cantilever supports at the platforms where the overhead tension ties would have conflicted with pedestrians or unsuitable rock was located.

The propped cantilevers have steel anchor plates that are attached to the rock face via rock bolts to support the tension ties and the compression strut beam (See Figure 6). Once the plates were installed, their locations were surveyed and this information, in conjunction with the topographic survey, was put into a 3D model in AutoCAD and then into a 3D steel model in ProSteel to finalize the geometry and connection details for the structural steel frame. The ProSteel software was able to lay out the complex structure and produce shop drawings while assembling all the connection details and the bill of materials for fabrication.

Figure 6. Strut beam plate and rock anchors.

The deck and walkway designs were similar to the bridge structures that made up the Treetop Adventures, one of the other attractions of the park. Considerations were focused on safety, aesthetics, and practicality. An example of this was the design of the railing and post system. The 1.64 ft wide deck has hand rails set at 4 ft above the deck with inclined posts, providing 2.62 ft of clearance between the hand rails (See Figure 7). This is wide enough to allow two people to pass each other, a requirement when visitors are stopping to enjoy the scenery of the canyon. The local fire department was consulted during the design, and these access requirements were deemed satisfactory in conjunction with the emergency plans.

Figure 7. Typical walkway and handrail system.

The key element of the guardrail and post system was to provide a safe but visually transparent guard. Glass panels was considered suitable at the beginning of the project, however, the maintenance required to keep this material clean and wind load consideration soon rejected the possibility of glass guardrail panels. Initially, a non-climbable guardrail using a system of horizontal tensioned cables was conceived and a prototype was developed and fabricated in the shop. This system provided the desired transparency but proved to have a number of deficiencies in its safety and was subsequently abandoned.

The final design utilizes a proprietary system X-TEND© available from Carl Stahl® DécorCable (See Figure 8). This system is a stainless steel woven wire mesh that can be designed to take on any tensioned 3D geometric shape and provided a barrier system that conformed to the ever changing geometry of the Cliffwalk. The woven wire mesh is treated with a black oxidation process and the mesh became virtually transparent when viewing from all angles, meeting the visual requirements of the project while providing a very durable and safe barrier. The barrier system also consists of more than 1476 ft of continuous 2” diameter polished stainless steel handrail along both sides of the entire walkway.

Figure 8. Stainless steel woven wire mesh.

There are two viewing platforms on the structure with glass decks to provide a more thrilling experience (See Figure 9). These glass decks have a baked-ceramic anti-skid coating to prevent them from becoming slippery in the wet West Coast rainforest. Glass guardrail panels are also installed at these glass deck locations for a better viewing experience.

Figure 9. Glass deck viewing platform.

4.0 Construction Development

Due to the unusual nature and extraordinary alignment configuration of the Cliffwalk, a high degree of accuracy was required for the construction layout as all walkway components were pre-fabricated off-site and the complete structure was never dry fit in the shop prior to shipping to site. Each piece of the Cliffwalk was custom built in a step-by-step process of surveying, engineering and fabricating with no two sections being alike.

In particular, erection of the 100 ft long semi-circular curved bridge presented a few challenges including construction site access and precise installation. Initially, it was envisioned that the entire curved bridge could be lowered into place in one piece, however, the limitations of crane size, crane position, and the existing trees quickly ruled out this option. The largest available crane that could be brought into the area of the park above the cliff near the curved bridge was the Link-Belt ATC-822, Telescopic Boom All Terrain Crane (See Figure 10), which at only 8.7 ft wide, still required one corner of the roof of one of the park buildings to be trimmed off in order to reach the site.

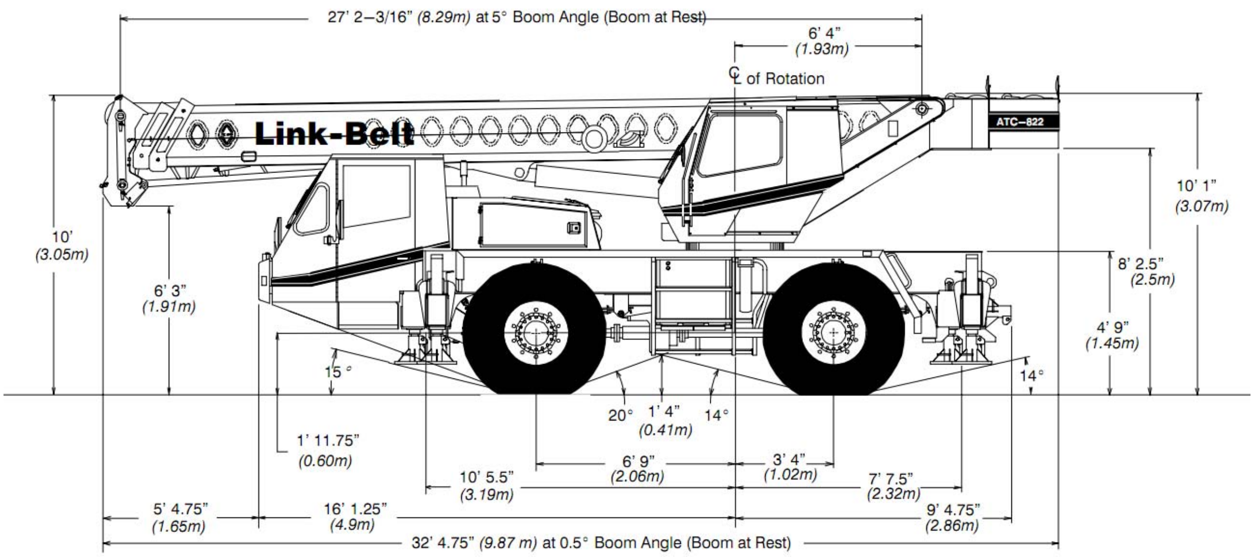

Figure 10. Crane configuration used for the curved bridge.

Existing large trees at both ends and also the middle of the curved bridge location prevented a straight lift of the entire bridge into the canyon. In the end, the curved bridge was divided into six segments and a staged erection plan was developed.

Staged construction loading of the bridge was modeled using SAP2000. Structure member sizes and geometry were input into the model and member groups were created for each of the construction segments. The modeling process was iterative as the required tensions in the cables were adjusted in each construction stage to achieve the required geometry. In addition, final model deflections due to total loading such as timber bridge deck, handrails and live loads were used to determine the required initial camber of the bridge to achieve a final level geometry. Also checked in the model were the rock face anchor bolt loads during installation and service as well as local stresses on the anchor plates at the two ends, which were modeled using finite elements.

A 25 stage erection plan was developed with details including erection weights, crane reaches, estimated required tension in the cables and bridge erection working point coordinates, which were checked using a total station during the time of erection.

Two temporary adjustable compression bracing members were designed to help maintain the geometry of the semi-circular curve while also resisting the tension in the main support cables prior to all the segments of the compression ring being installed (See Figure 11). These bracing members were large turnbuckles with an adjustment length of ±6" and the threaded portion of the member was reinforced with an outer sleeve to prevent buckling. The braces were pinned to a temporary anchor in the rock face at approximately the same elevation as the top chord / deck of the curved bridge, and they were bolted at the other end to the guardrail post holes at the bridge floor beam frames. They were set horizontally rather than with a vertical angle in order to simplify any geometry adjustments and to be able to better predict the loading in the cables during the construction stages.

Figure 11. Temporary bracing members (red) for the construction of the curved bridge.

The construction started with the installation of the end segments which were cantilevered from the rock face (See Figure 12). The steel plates of these end segments were anchored with five rock bolts that were drilled and grouted at the abutment location of the curved bridge on the cliff face. The Link-Belt crane was used to support the bridge end segments while a jib crane was used to install the compression bracing and the first set of cables. The compression bracing and cables were adjusted throughout to bring the geometry of the bridge into position. The process of installing the segments and adjusting the cables was repeated for all six bridge segments.


Figure 12. Erection of the curved bridge.

4.1 Load Testing

Nondestructive load testing was performed on the curved bridge and on two of the straight bridge sections to evaluate the load capacity and deflections of the structure. The chosen straight bridge sections are supported by a strut beam bolted to the rock face which produces the largest reaction comparing to other strut beam foundations on the project. The simulated load applied for the testing was equivalent to 0.6 psi, which was the design live loading and was achieved by filling 45-gallon barrels with potable water (See Figure 13).


Figure 13. Load testing the curved bridge with water barrels.

Instrumentation used in the testing included vibrating wire strain gauges, thermometers, tilt meters and a cable tension meter. Every third barrel was initially filled as part of the loading sequence while readings were taken from the instrumentation and a visual inspection was conducted until all the barrels are filled. Both the straight bridges and curved bridge were unloaded from one end to simulate checkerboard loading effects. The structures performed very well and the measured forces in the cables were found to agree closely with the predicted values.

5.0 Closure

The challenging design and construction of the Cliffwalk resulted in a unique steel bridge structure along the cliff face that reinforces the sustainable tourism model already in place at the Capilano Suspension Bridge Park. The project demonstrates that teamwork on infrastructure projects is the best foundation for success as this project was truly a collaborative effort from start to finish by all parties involved. It illustrates that structures can be successfully constructed to serve a purpose that goes above and beyond the utilitarian nature of most modern bridges. Opened on June 3, 2011 the Cliffwalk has received many accolades with enormous amount of media attention and Cliffwalk was the winner of 2011 Commercial Building Award of Excellence by the Real Estate Board of Greater Vancouver.

Figure 14. Constructed curved bridge testing the curved bridge with water barrels.