A CRITICAL ANALYSIS OF THE SECOND BRIDGE ACROSS THE PANAMA CANAL: THE CENTENNIAL BRIDGE

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Abstract: This conference paper represents an analysis of the second bridge across the Panama Canal, the Centennial Bridge. Information is provided on the background to the bridge and more specifically why the bridge was constructed. An in depth aesthetic analysis is performed on the bridge using the ten guidelines set out by Fritz Leonhardt detailing success and elegance achieved in the design for such a large structure. The structural arrangement is then detailed to convey how the bridge performs under the various loading conditions and what specific structural components were selected for the bridge. The author provides estimates of the dead, super-imposed dead and live loads subjected to the bridge and also considers the effects of seismic activity on the bridge. The construction process is outlined and the primary stages are discussed. Subsequently a brief explanation of the durability of the bridge is given. The bridge is unlikely to undergo major changes in the future, but, with the increasing traffic flowing along the Pan American Highway it is predicted that a third bridge may well be required in the future.

Keywords: centennial Bridge, Puente Centenario, aesthetics, structure

1 Introduction

The Panama Canal represents one of the greatest engineering achievements by man. The canal was completed in 1914 and provides a navigational link between the Atlantic and Pacific Oceans by cutting through a narrow section of The Republic of Panama. However, it was not until 1962 that a canal bridge crossing was developed. Puente de Las Americas (Bridge of the Americas) represented a four lane bridge crossing that was sufficient for the volumes of traffic for that time. However, with the construction of the new Pan American Highway and the continued expansion of Panama City, traffic volumes reached 35000 vehicles per day in 2004 in contrast to 9500 vehicles per day when the bridge first opened in 1962. Subsequently, the bridge could not cope with the increased traffic demands [1]. The Panamanian Government recognised the problem and proposed a second crossing for the Panama Canal that would be called Puente Centenario (Centennial Bridge) to represent 100 years of Panamanian independence from Columbia. The construction of the bridge, in conjunction with the new freeway connecting Arajhan (west) to Cero Patacon (east), was hoped to alleviate the traffic congestion observed around the existing bridge and to facilitate the development of the western side of Panama [2].

The Panamanian government specified a set of criteria for the design of the new bridge that included a 6 lane traffic capacity, central pedestrian walkway and 100 year expected service [2]. However, there were two central considerations for the design and construction of the Centennial Bridge. First, canal traffic could not be interrupted at any point during the construction or completion of the bridge. Also, the bridge had to have sufficient navigational clearance (80m high and 110 m wide) to allow the large crane Titan, which is used for canal lock maintenance, to pass below the bridge [1, 3]. To provide the required navigational clearance an innovative and large structural design had to be formulated and the construction methods had to be selected and planned carefully. Secondly, were the challenges presented by the varied founding conditions discovered along the bridge and also the prevalent history of seismic activity in the area [4].
The bridge was designed by Guatemalan architect Miguel Rosales, who developed a single plane cable-stayed bridge with a cast in place concrete box girder that would become the longest and highest cable-stayed bridge over a water way in the western hemisphere (Figure 1). The bridge forms a very large structure with a main central span of 420m and a total length of approximately 1052m (figure 2).

The Centennial Bridge is located 15km north of the Bridge of the Americas, 22km from Panama City close to the Pedro Miguel locks. The bridge was financed by the Panama Ministry of Public Works (MOP) who awarded the design contract to TY Lin International, the construction contract to Bilfinger Berger, the detailed design contract to Leonhardt, Andrau und Partner (LAP) and the project management contract to international consulting group COWI. The bridge was inaugurated by the Panamanian President on 15th August 2004 and was opened to traffic on 1st September 2005 subsequent to the completion of the two approach roads.

2 Aesthetics

Aesthetics is of central importance in the design of bridges. The significant scale of most bridges, in particular cable-stayed bridges, provides a substantial impact on the aesthetics of the surrounding environment. Although the primary function of a bridge is still to safely transport traffic from one place to another in as economically efficient manner as possible, a bridge should also provide an aesthetically pleasing structure for the surrounding area [5]. Bridge aesthetics, therefore, forms one of the central design considerations for bridge engineers and architects formulating new innovative designs. Bridge aesthetics are concerned with the emotional response that the structure evokes in a viewer and consequently bridge engineers have often found it difficult to provide a rational analysis of bridge aesthetics.

Many attempts have been made to develop a set of rules for bridge aesthetics [6] based on the premise that, although the theory of aesthetics defies rational analysis, a framework can be used to facilitate the design and evaluation of structures [7]. One of the leading bridge engineers, who developed such a framework, was Fritz Leonhardt. Leonhardt outlined 10 area of importance for bridge aesthetics; Fulfilment of function, proportions, order, refinements, integration into the environment, texture, colour, character, complexity and nature[7]. The author will follow these guidelines to critically analyse the aesthetics of Puente Centenario.

2.1 Aesthetic analyses of the Centennial Bridge

Leonhardt suggests that, primarily, a bridge should fulfil its purpose, by showing clearly how it works in order to create a sense of stability and safety. The bridge should highlight its structure in a pure, clear and simplistic manner to achieve this. Cable-stayed bridges are a particular bridge load bearing system that conveys it function through its pure structural simplicity. More specifically, the Centennial Bridge reveals its structural form through a single plane, single pole cable-stayed bridge that has three main structural elements: box girder bridge deck, towers and cable stays. The structural system is easily interpreted where the deck loads are carried directly in tension in the stay cables back to the towers which then transfer the loads down through the two towers in the foundations. The structural system should also be visible from the view of the traffic moving across the bridge to allow bridge users to experience the aesthetic of the bridge and also ensure that confidence in the stability of the structure is achieved. Generally, to achieve this bridge designer’s use two planes of cables that create an envelope for the traffic to move through to increase the feeling of safety. However, for the centennial bridge there is a central single plane of cables and, therefore, the traffic moves along either side of the cable on the cantilevered bridge deck (figure 3). Although this may suggest an area where the bridge design does not convey its function through stability it provides a complex variation to the otherwise simple structure that can offer aesthetic improvements to the structure. This underlines Leonhardt’s guideline of complexity where he...
suggests that a small amount of complexity can be pleasing, but, it should be kept to a minimum [7].

The proportions of a bridge e.g. height width and breadth, masses and voids, closed surfaces and, and light and dark have also been highlighted in Leonhardt’s bridge aesthetic guidelines. Leonhardt suggests that harmonious dimensions must be achieved in order to design a beautiful structure. Due to the 80m navigational requirements for the Centennial Bridge, the large distance that the bridge had to cross and the wide deck required for 6 lanes of highway traffic the design of the proportions of the structure and its individual elements was of paramount concern. The towers, as one of the major structural components, were required to be proportioned very carefully. Using a single pole tower system (figure 3) it was crucial that the towers were not too slender as this could give of an impression of weakness and would look incorrect in relation to the large length and breadth dimensions of the concrete box girder. Figure 4 conveys that the proportion of the towers appear correct and conveys an image of strength. The large navigational clearance required meant that the overall bridge height would have to be proportioned similarly. The top of the towers reach a height of +211m (184m above the +27m water level) which conveys harmony between the voids below and above the deck. The piers have also been shaped to harmonise with the tower sections.

Leonhardt underlined that order within the bridge was also required to improve the aesthetic. He underlined that bridges should convey order in their lines and edges. This is a particularly important consideration for the Centennial Bridge due to the cables stays. Many stay cable arrangements used for this type of load bearing system convey crossing of the lines of the cables from oblique views. However, the Centennial Bridge uses a single plane semi harp design which has the advantage that the cables will never cross when viewed from different angles. This reveals a clear ordered arrangement of the cables enhancing the aesthetic appearance. Another example of good order in the bridge is that has a continuous box girder element that does not change throughout the length for the structure. Symmetry and repetition of the structure also provides good order for the bridge. The main section of the bridge consists of three spans, the central span of 420m and mirrored spans of 200m either side (figure 2). The cable two towers are geometrically identical and they also support matching cable stay arrangements (figure 2). Similarly, the piers that support the viaduct to the east and west of the main section have the same plan sections; however, they vary in height due to the changes in topography beneath the bridge. Despite this, the piers convey repletion of similar structural elements. The symmetry and repetition observed in the Centennial Bridge provide rhythm in the visual appearance of the structure, which creates satisfaction for the viewer.

Leonhardt describes how refinements can be used to improve the aesthetic quality of a bridge. The Centennial Bridge portrays a number of refinements in its structure. Some of these refinements are linked to the optical illusions that are created by using large structural elements with straight edges. To prevent this optical illusion forming for the towers, where straight edges would result in the towers appearing wider at the top when viewed from below, the towers are tapered towards the top. Another optical illusion that was prevented was the sagging that would have been perceived if a straight deck was used for the long spans on the Centennial Bridge. To achieve this, a centred 600m section was given a slight camber, 10,000m vertical radius [1], to ensure that the long bridge deck is viewed as straight from a distance (figure 5). The spans of the viaduct highlight a further refinement of the bridge where the spans decrease as they approach the slopes on either side of the bridge. Refinements have also been performed to consider the effects of light and shadow on the structure where the wide cantilever deck casts a shadow over much of the box girder giving the deck the desired light and slender appearance. A final refinement that can be observed by the traffic and pedestrians using the bridge is provided by the view of the anchorage system on the front face of the towers (figure 6). These anchorages are emphasised by a groove that is extended beyond the anchorage zone which draws attention to the structural purpose of the cables. A suggested further refinement that could improve the aesthetic of the bridge could be to provide a smooth finish on the bottom of the continuous box girder as this forms one of the most important view’s of the bridge for freight traffic using the canal. This was probably not attempted due to the cost of providing a smooth finish for the box girder that stretches over 1km.
Leonhardt underlines the importance of the integration into the environment of bridges and this particular guideline has been considered the most important by many other authors [8]. Cable-stayed bridges in general provide an excellent load bearing system that offers sufficient flexibility for integrating the structure into its environment through its range of configurations of deck, tower and cables. The Centennial Bridge spans a large valley that the Panama Canal flows through and due to the flexibility of cable-stayed bridge design this structural system was a very appropriate choice to ensure good integration into the environment.

The required scale of the bridge also meant that integration into the environment was going to be essential for producing an aesthetically pleasing structure. First the most significant feature of the surrounding environment is the Panama Canal. The canal itself is a large engineering project and also has a significant scale and, therefore, the bridge that crosses it should relate well to this. Consequently, this explains why such a large structure can blend seamlessly in with the surrounding environment. In addition to this, the single semi harp cable arrangement and the relatively slender proportioned continuous deck and towers create an elegant and transparent structure that is unobtrusive to the surrounding environment. The successful integration into the environment can be summarised by a “surreal feeling that towers and stay formations are those of sailboats that hover over the canal. The landscape of the area where the bridge stands is mainly that of rainforest. With this picturesque background, the beautiful Centennial Bridge is a welcome addition that adds glamour to the scenery with its sleek and graceful appearance” [2 p.23].

The choice of material, surface texture and colour provide additional considerations that can facilitate the integration of the bridge into its surrounding environment. The Centennial Bridge has a concrete deck and abutments. These structural elements appear to have a rough finish which is advised by Leonhardt [7]. The concrete is not coloured, but, reflects a beautiful white colour during the day (figure 4). The concrete deck also has fascia beams that have a smooth finish which emphasizes the location of the bridge deck. The colour of the cable is an important consideration because it impacts upon the appearance of light on the bridge. The Centennial Bridge has white cables. White cables reflect the light of any colour and, therefore, the appearance is constantly changing depending on the colour of light being reflected by the cables.

The character of the Centennial Bridge was absolutely paramount to the success of the bridge as an aesthetic structure. The Panama Canal is symbolic of The Republic of Panama and subsequently the Centennial Bridge had to be worthy of crossing it. The sheer scale of the bridge provides character in abundance, however, it is the way in which this large structure is delivered in a light and transparent form that builds the character for the Centennial Bridge and renders it worthy to provide the second crossing of the Panama Canal.

Leonhardt’s final guideline is that a consideration of nature can improve the aesthetic. The centennial bridge design does not appear to have incorporated nature into the design in any specific way. This was possibly due to the often complex organic forms that are observed in structures that use nature to drive design. This would contrast the criteria specified for this bridges where it was important to keep the structure as simple as possible.

Figure 7: Elevation showing the structural arrangement of the Centennial Bridge

3 Structural arrangement

The Centennial Bridge has a structure consisting of a single pole single plane cable-stayed arrangement (figure 7). A continuous box girder carries the traffic across the 1052m distance between abutments E1 and E2. The deck is supported along its length by the two towers T1 and T2 as well as the secondary support provided by piers P1, P2, P3 and P4 located on the east and west sides of the canal. In addition to the support provided by the towers and piers the deck is supported by a single plane cable stay configuration suspended from the two towers.

The design of the layout of the stays for cable-stayed bridges represents one of the most important considerations in the design of cable-stayed bridges [9]. There are a number of options available to bridge designers most notably the harp and fan arrangements. The harp pattern represents the most aesthetically sound arrangement where there is no crossing of the cables from oblique views; however, from an economic and structural point of view it is not the most efficient configuration. The fan pattern theoretically brings all the cables together at the top of the pylon, which has a number of advantages including the decreased horizontal force induced by the cable in the deck. Although it has been suggested that the crossing of cables often found in fan patterns for bridges is not a problem for large span bridges [9] like the Centennial Bridge, there remains a specific limitation of using this pattern. This problem is that it is not practically possible to bring all the cables together at the same point at the top of the pylon and, therefore, spreading of the anchorage zones creates a highly stressed region at the top of the pylon. This zone subsequently requires complicated and costly methods of construction that also detract from the elegance of the structure and, therefore, explains why the fan pattern would not have been selected for the centennial bridge.

The cable stays are arranged in a semi-harp configuration. This arrangement does not provide the most efficient structural arrangement; however, for the
aesthetic purposes underlined in the aesthetic analyses it is reasonable to specify this cable stay arrangement to improve the visual appearance of the bridge. The semi-harp pattern represents an arrangement that combines the layouts of the harp and fan systems. It combines many of the advantages of both these patterns whilst also eradicating many of the disadvantages. The decision to use the semi-harp pattern for the centennial bridge allowed the stays to be spread out in the upper region of the pylons, which would greatly facilitate the good design of the anchorage details without decreasing the depth and integrity of the pylon structure. Another advantage that the semi-harp pattern introduced was that the cables near the top of the pylons are at a greater inclination, which facilitates the reduction in the required stiffness of the connection between the pylons and the deck.

The first modern cable-stayed bridges only had a small number of stays, which created large distances between the elastic supports. This meant that very stiff bridge decks were required. As this bridge configuration has developed multiple-stay bridges have been introduced, which decrease the distance between the elastic supports and subsequently facilitate the use of decks with reduced stiffness. This allows for more slender decks to be used, which have obvious aesthetic and structural advantages linked to the lightness.

The Centennial Bridge was designed with a multiple-stay configuration to utilize these specific advantages. The cable stays are closely spaced (figure 3) and subsequently the bending in the deck is greatly reduced. This reduction in bending allows the bridge deck to be more slender. However, as a consequence, of using the single plane cable-stayed arrangement and the large width required (34m) for the six lane capacity road surface, the bridge deck had to have sufficient torsional stiffness to support the weights of the cantilevered bridge deck and the loads that it carries. Generally, to achieve high torsional stiffness box sections provide a good option [9]. The Centennial Bridge utilizes a box girder to achieve this torsional stiffness that is supported on transverse beams at 6m centers to increase the stiffness of the deck. The design decision to use a single plane arrangement represents an inefficient structural strategy because of the additional stiffness required in the deck. However, as described in the aesthetic analyses of the Centennial Bridge the single plane arrangement provides aesthetic qualities for the bridge and, therefore, the inefficient design of the stiff box girder can be justified.

To provide sufficient torsional stiffness in the deck careful detailing of the pier-deck connection was crucial. The torsional stiffness and lateral restraints was achieved by fixing the towers longitudinally to the deck [10], which produced a uniform structural frame. The box girder is supported vertically at all the piers and the two abutments by multi-directional pot bearings [10]. These pot bearings accommodate the estimated deck movements of 16 inches and also limit the ingress of water because of the rubber seal commonly used for this type of bearing. P3 and P4 also have hold down cables that connect to the foot of the piers. Horizontally the box girder is supported by transversally fixed supports at P1, P3 and P4. This is achieved by using a shear key that penetrates through from the girder diaphragm into the pier top [1]. In the longitudinal direction all the supports are equipped with moveable bearings [1]. Expansion joints, which allow horizontal movement to occur within the plane of the deck, are used only at abutments E1 and E2. This is probably because expansion joints often fill up with debris, and, therefore, the uniform fixed connection between the towers and the deck offers a better solution.

This structural arrangement is effective because it reduces the restraint forces caused by wind loading and seismic effects [1]. This is achieved by the proportional distribution of the transverse, seismic and wind loads to the towers fixed supports to the deck and the shear keys that are located at the top of P1, P3 and P4.

4 Loading

The most important loadings that need to be considered for the design are dead, superimposed dead, and live loads. For the centennial bridge seismic effects also represent an important consideration in addition to the generic loading conditions required for bridge design.

4.1 Dead and super-imposed dead loads

The dead load for the bridge deck was calculated to be 416MN over the 820m length supported by the cable stays (figure 7). The superimposed dead load, assuming a 120mm thick layer of asphalt was calculated to be 77.3MN. For dead loads, as specified by BS5400 partial factors are applied to these loads. $\gamma_{fl}=1.05$ for ultimate limit state (ULS) and $\gamma_{fl}=1$ at service limit state (SLS). Super-imposed dead loads are factored at $\gamma_{d}=1.75$ for ULS and $\gamma_{d}=1.20$ for SLS. The super-imposed partial factors are considerably larger than those for dead loads because it is certain that super-imposed loads will be replaced in the lifetime of the bridge and, therefore, it is probable that the bridge will be subjected to a different super-imposed load.

4.2 Live loads

Eurocode design suggests that the first consideration for live loads is to define the number of notional lanes. The carriageway had an overall width of 34m with a central pedestrian walkway of 5.5m and, therefore, the number of notional lanes was found to be 8 in table 4.2 [11]. The lane width was therefore calculated to be 3.56m.

4.3 HA loading

HA loading represents uniformly-distributed load acting over a notional lane in combination with a knife-edges load (KEL) located at the adverse position within the notional lane. This loading considers the effects of fast moving traffic. The loaded length considered for the design of the bridge would vary because different scenarios need to be analyzed to identify the most onerous load case. For the Centennial Bridge the most onerous load cases are likely to be
observed when the length between P3 and T1 is fully loaded and the rest is not loaded and secondly when the length between T1 and T2 is fully loaded and the sides remain unloaded. For the first case the loaded length was 200m and therefore the load is 12kN/m or 3.37kN/m² for the 34.1m wide deck used for the Centennial Bridge. For the second case the load is 9kN/m which subsequently renders a load of 2.5kN.m² for the full width of the Centennial Bridge. For each of these cases a KEL of 120kN would be considered at the central location of the loaded length.

4.3 Seismic loads

The location of the Centennial Bridge meant that the bridge would have to withstand the effects of seismic activity. The seismic design of the bridge considered two different scenarios. A 1 in 500 year as well as a 1 in 2500 year earthquake event were considered to ensure that the bridge had sufficient stability to withstand such events. The bridge was carefully tuned to reduce the effects of the loads produced in earthquake events.

5 Serviceability

There is very little literature on the serviceability methods used for the Centennial Bridge. However, it is likely that a network of sensors are used to monitor the moments, axial stresses, foundation settlements, deflections in the deck and stresses in the pre-stressed cables. This would allow the serviceability of the bridge to be continually monitored and provide current data on the condition of the bridge.

6 Construction

The Centennial Bridge was constructed using a fast track process in order to ensure that the bridge was completed in time to commemorate 100 years of Panamanian independence from Columbia. As well as the tight schedule the construction team faced major challenges from the founding conditions and seismic activity present in the area. The concrete structures that comprise the cable-stayed bridge were predominantly constructed from local material. The concrete used for the bridge was designed for the specific strength demands of the individual structural components, e.g. piles constructed using 30MPa, foundations using 35MPa, piers and towers using 45MPa and finally the superstructure using 50MPa [1].

The construction process began with a pile investigation of the ground conditions at tower T1 and subsequently at piers P2 and P3 (figure 7). The results conveyed that there were variable ground conditions along the length of the bridge where a block of basalt was found on the east bank that would provide supporting stratum that could directly support the bridge. In contrast, along the west bank, a soft formation of clay shale constituting of sandstone, basalt and ash was revealed and presented the possibility of landslides and, therefore, could not provide direct support for the bridge. Due to the varying founding conditions different foundation methods were required for the abutments, piers and towers along the length of the bridge. There were two different foundation methods used for to support the bridge. Direct foundations were used for abutment E1 and E2, piers P1 and P4, and tower T2 as there was sufficient supporting stratum in these locations. In contrast deep piled foundations were used for piers P2 and P3 and tower T1 to provide sufficient support in these unstable locations. Both types of foundations were constructed using conventional methods.

The towers, approach structure and piers were all built at the same time to ensure a quick construction period for the bridge. The towers are identical apart from the foundations and were cast in place using climbing formwork (figure 8). The formwork used was flexible so that it could facilitate the changes in geometry of the towers as they tapered towards the top. The tower shaft was divided into 48 segments with a standard height of 4m; however, where the towers deck intersected the segment heights were decreased because they had to be adjusted to facilitate the anchorage points of the stay cables. A four day cycle was used to produce each individual segment; however, at the areas where anchorage points were present the process was more time consuming because of the pre-stressing operations required and the reduced accessibility [1]. This four day cycle facilitated the fast track construction process required to produce the bridge on time. The towers were constructed on either side of the canal to avoid having to construct deep water foundations, which are costly and it was also important to provide enough space for freight traffic to pass between the towers. Steel formers were used to cast the pier shafts in place and when an individual segment had hardened they would be moved to a higher level to cast the next section. As mentioned previously a shear key is used at piers P1, P3 and P4. To transfer the horizontal forces from the shear key into the pier shaft the pier tables were pre-stressed transversally. These tables took three months to construct. The approach viaduct began with construction on the east side P4-E2 and subsequently the west side viaduct was built in three stages from E1-P3. The box girder deck for the approach viaduct was constructed using custom built formwork, which was lifted into place to cast the deck.
construction method as it does not require temporary structures to be built to support the bridge. It is probable that this was one of the main reasons this method was used; however, the main advantage that this construction method provides is that it would not disrupt the flow of traffic along the canal during the construction process, which was one of the main specifications underlined at the beginning of the project. The deck was cast in place using 4 form travellers, 2 for each tower. 128 cables were used to suspend the deck using this method of construction. The cantilever construction of the deck began shortly after the towers exceeded the height of the deck and work was continually carried out on both sides to once again ensure an efficient construction process.

7 Natural Frequency

The Centennial Bridge has a central pedestrian path and, therefore, the effects of the vibrations caused by people walking across the bridge need to be considered. The effects of vibrations in bridges are very important at high and low frequencies. High frequencies in excess of 75Hz cause undesired physiological effects whilst low frequencies below 5Hz are critical and a consideration of the is required to limit the vertical accelerations on the bridge. The Rayleigh-Ritz method provides a procedure for engineers to calculate the fundamental natural frequency of the bridge frequency of a bridge (Equation 1: Fundamental natural frequency). For this analysis the bridge was investigated for both the clamped and clamped-pinned modes to make sure that the fundamental frequency is above 5Hz. The mass used for this formula is the dead load of the bridge, including super-imposed dead loads. It does not consider the live loads subjected to the bridge. The calculation shown below convey that the bridge's natural frequency is above 5Hz for both cases and, therefore, the bridge will not encounter problems from vibrations and oscillation at the ultimate limit state.

\[ w_n = \beta_n \sqrt{\frac{EI}{ml^3}} \]

Equation 1: Fundamental natural frequency

Where \( \beta_n = 22.37 \) clamp-clamp case, \( \beta_n = 15.42 \) clamp-pin, \( l = 420\text{m} \) (main central span), \( E = 200 \times 10^9 \text{ N/m}^2 \), \( I = 912.5\text{m}^4 \), and \( m = 51.7 \times 10^3 \text{ kg/m} \)

Clamp-clamp case:

\[ w_n = 7.53\text{Hz} \]

Clamp-pine case:

\[ w_n = 5.19\text{Hz} \]

8 Durability

The durability of the cable stays for the Centennial Bridge is an important factor to consider due to their primary structural purpose and their open exposure to the environment. The area has high humidity and, therefore, there is a large amount of moisture in the air. This can corrode the cable stays substantially decreasing the strength of the cables. To provide corrosive protection the wires that make up the cable stays are galvanized through hot dipping and subsequently are concealed in extruded polyethylene sheaths. The voids between each of the wires are filled with wax to provide further protection from the humid atmosphere. These protective strategies ensure that the structural integrity of the cable stays remains intact for the design life of the bridge. However, it is important to note that should an individual cable stay experience reduction in strength because of corrosive activity they would be easily replaced because the Centennial Bridge is a multiple-stay cable stayed bridge where there is sufficient redundancy available to temporarily remove and replace existing stays safely. Another common problem related to the durability of cable stayed bridges is linked to the corrosion of the concrete deck. This is often caused by the ingress of water and de-icing salts into cracks in the concrete. This then corrodes the steel reinforcement present in the deck leading to reduction in the structural integrity of the deck. However, with the warm climate present in the location of the bridge the action of corrosion caused by de-icing salts is unlikely to be a concern to the Centennial Bridge.

9 Future changes

The future changes likely to be observed for the Centennial Bridge are predominantly linked to the maintenance of the bridge. These may include resurfacing of the road, replacement of cable stays and the repair of corroded steel within the deck. It is more likely that with the increasing demands of traffic within the area that, similar to Puente de las Americas, the Centennial Bridge may encounter capacity problems. Consequently, it is probable that in the future a third crossing for the Panama Canal could be required.

10 Conclusion

The Centennial Bridge represents a bridge with character suitable for providing the second crossing over the Panama Canal. An aesthetic analysis has underlined the specific factors that facilitated the design in achieving aesthetic quality. The design and construction of the bridge had to cater for the large scale of the bridge required to provide the 80m clearance to the bridge deck required to enable uninterrupted access to the canal for freight traffic and the gigantic canal crane Titan. The
structural design utilized a single plane multiple-stay cable stayed bridge to fulfill these design requirements whilst also ensuring that a visually aesthetic structure was produced that was integrated into the environment. The bridge was made from three primary components; the towers, box girder deck and cable stays, but, also had an approach viaduct connecting the Pan American Highway from the east and west of the canal. The design of the bridge also considered the difficult founding conditions found on site and the load effects of seismic activity in the area. The construction process was vital for ensuring the success of the Centennial Bridge as it not only had to be delivered on time for the commemoration of 100 years of Panamanian independence from Columbia but also had to ensure that the construction method did not restrict freight traffic at any point because of the importance to the local and global economies of freight moving through the Canal. A free cantilevering method was used to construct the superstructure from the pre constructed towers. This represented a cost effective approach that required minimal volumes of equipment. Overall the bridge represents a successful design and construction project that provides a relatively efficient structure to provide a very large structure suitable not only to carry the loads subjected to the bridge but also facilitates the formation of an elegant and light structure that is integrated into the environment with grace.

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