

CRITICAL ANALYSIS OF SUNSHINE SKYWAY BRIDGE

Adam T Sayers

University of Bath

Abstract: This article provides a detailed analysis of the cable-stayed bridge, Sunshine Skyway, located in the Tampa Bay region of Florida. It includes critiques of its structure, aesthetic form, and construction giving an indication of how successful it has been since its construction in 1987.

Keywords: Sunshine Skyway
Cable-Stayed
Pre-cast Concrete box sections
Pre-stressed tendons
Aesthetics

1 General Introduction

The Sunshine Skyway Bridge is one of the world's longest cable-stayed concrete bridges, with an overall length of 8.9 km. It forms part of the US 19 Highway, connecting St. Petersburg and Palmetto in the Tampa Bay region of the state of Florida. Construction of the bridge began in 1982 and was completed on February 7, 1987, at a total cost of \$245 million. It was designed by the Figg & Muller Engineering Group, and built by the American Bridge Company.

The bridge was commissioned to replace a steel cantilever bridge of the same name after part of it was destroyed in 1980. This was the result of a collision between the freighter *Summit Venture* and one of the piers during a severe storm leading to the deaths of 35 people. As a result of this, the safety of the bridge and the need to prevent a similar disaster from occurring became one of the primary goals during the design of the new bridge.

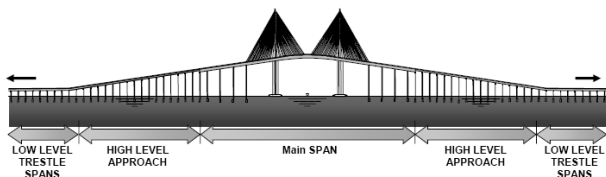


Figure.1: Sunshine Skyway geometry [1]

The whole bridge is constructed of steel and pre-cast concrete sections. Figure 1 above shows how the bridge consists of three different sections. The low level

trestle spans are all that remains of the original bridge built during the 1950's. The high level approach sees the level of the bridge raise up to give the necessary clearance for ships. Finally there is the main cable-stayed section, which has the longest span of 366m, and a clearance of 59m above the water. This main span of the bridge is supported by forty-two steel cable-stays running along the center line of the bridge which are connected to two slender concrete pylons that rise a further 76m above the deck.

2 Aesthetics

The aesthetic appeal of a bridge plays a vital role in the overall success of a structure. When the construction of the bridge was completed in 1987 it was hailed as being a triumph in bridge design and has won numerous awards as a result. The following statement from the New York Times is indicative of this: 'from an esthetic standpoint [the Sunshine Skyway Bridge] may well rank as the most impressive piece of large-scale bridge design in this country in half a century.' [2] In order to quantify the aesthetics of a bridge Fritz Leonhardt, one of the most prolific bridge engineers of the 20th century set out a series of areas to be considered which are summarised below.

2.1 Fulfillment of Function

The Sunshine Skyway Bridge is a perfect example of the design philosophy, 'form follows function.' [3] This is where the combination of simple and efficient structural systems together with economic construction leads to an elegant and pleasing solution. The overall structure is

simple and all of its components serve an important structural role as well as adding to the aesthetic. It is clear to anyone using the bridge how the loads are transferred into the pylons through the cables. This imparts a feeling of confidence towards the structure and so those using it will not be intimidated by it.

2.2 Proportions

The proportions of a bridge can help to imply a sense of order whether it is through the use of voids and solids, or the relative sizes of the members. In the case of Sunshine Skyway the use of proportion has been fairly successful however, it has failed in some areas. When looking at the bridge on profile such as in fig:2 below we can see that as the height of the bridge increases the length of the spans also increases and although the aspect ratio does not stay exactly the same we do get a sense of



Figure 2: The main span at dusk in all its glory.

rationality about it. The depth of the bridge deck is relatively slender and when combined with the pair of slender pylons that soar into the air and the steel cable stays we get a feel of lightness about the whole structure. The downfall of this structure appears when viewing the bridge from a more head-on angle. The widths of the central supporting piers are over double that of the pylons



Figure 3: Oblique view clearly showing the disparity between the widths of the piers and pylons

that sit on top of them leading to a rather harsh discontinuity in the flow of the structure. This problem is clearly demonstrated in fig 3 below.

2.3 Order

One of the greatest successes of the look of this bridge is its free flowing nature and perfect order. As you pass your eye over the top of the deck the structural lines remain unbroken for the entire length of the bridge. This is achieved through the use of pre-cast concrete sections that are tied together using hidden post-tensioned steel cables to give an uninterrupted soffit line. The solid concrete crash barrier serves to create a perfect line along the top of the deck.

An aesthetic failing of many cable-stayed bridges occurs when multiple lines of cables are used to support the structure. When viewed from oblique angles the cables can give the appearance of crisscrossing making the structure look cluttered and awkward. The designers of Sunshine Skyway however, have decided to avoid this issue altogether by using just a single line of cables. This does however, compromise the structural efficiency of the bridge due to a reduction in torsional strength, but it was decided the visual benefits would warrant this. The overall effect of these clean, crisp edges and ordered structure is one of extreme elegance. A semi-harp configuration has been used for the cables. This is not

2.4 Refinements

On a whole there have not been many more refinements to this structure, other than those already mentioned that add to its appearance. However, certain refinements could be made to improve matters. In order to address the problem pointed out with the proportions of the piers and the pylons, the pylons could have been tapered out towards the base and the piers could taper in towards the top, so that the disparity between the two would have been reduced.

2.5 Integration into the Environment.

It is important to consider how a bridge interacts with its surroundings and Sunshine skyway is no exception. The use of a cable-stayed bridge is an obvious choice when crossing a large expanse of open water as its sleek, slender profile and triangular plane of cables give it look of a sailed ship skimming across the water when viewed from a distance. Also the subtleness of the cables during certain times of the day allow for uninterrupted beautiful views such as the one seen in fig.2.

2.6 Texture

In order to distinguish between the different structural elements of the bridge and given each its own identity, a clever, but subtle use of texture has been used. The concrete of the piers has been given a rough texture which continues through to the two pylons at the main span, where as the concrete elements that form the deck and the crash barrier have a smooth finish.

2.7 Colour/Character

There are some extremely successful uses of colour and lighting with this bridge that helped it to develop its own sense of character. Probably the most important part of the bridge both structurally and aesthetically are the cable stays that support the structure over its longest span. In some cable-stayed bridges colour is used to hide them to give the impression that the deck is floating. However, in this case the designers have decided to accentuate their presence and celebrate the role that they play by painting them a 'brilliant yellow.' This causes them stand out against both the sky and the rest of the structure. The choice of colour is symbolic not only of the name of bridge but also of the name of the state in which it resides, 'The Sunshine State.' As a result the bridge has become an icon of the state and is frequented by many tourists. Further emphasis is placed on the cables during the night time through the use of light as shown in fig.4. Strategically placed lights high-light the cables whilst leaving the rest of the bridge in relative darkness allowing them to be seen from miles away. This gives a wonderful



Figure 4: The Bridge at night.

effect similar to that of the Alamillo Bridge in Seville where the main pylon is high-lighted.

The positions of the piers at the centre of the deck with large overhangs on either side gives rise to a large amount of shadow being cast onto them. Consequently the piers appear to be a lot more slender than in reality further helping to boost the impression of weightlessness that this bridge is trying to convey.

3 Structural Features

3.1 Main Span

The main span of bridge deck is constructed using pre-cast concrete box-sections with a profile as shown in fig.6. Each piece has a width of 29m a depth of 4.3m and weighs around 200t. The top of each of the sections forms the actual roadway. The use of pre-cast sections is far preferred to in-situ casting due the large costs involved

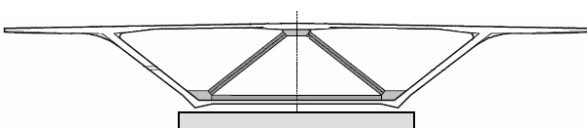


Figure 6: Cross-section of concrete sections for main span

both in terms of money and time. Each of these sections is tied to the next by using internal post tensioning cables. These are set within the webs and flanges of the section running longitudinally throughout the length of the bridge. The cable stays are positioned on every second section to provide additional support. This greatly reduces the amount of pre-stress required to hold the structure together. Post-tensioning cables are included in the bottom flange of the section in order to provide more resistance to sagging moments. Shear keys are located along the edges where two sections meet to help transfer the shear forces. Diaphragms will be added to the sections over the supports to increase the stiffness of the structure and to reduce the likelihood of shear punching. The use of pre-cast sections has not however, been used to its full potential in this case. The current design utilises box-sections of constant cross-section through-out the entire length of the bridge and so the top and bottom flanges are designed to carry both the maximum hogging moments as well as the maximum sagging moments. Clearly, this is a waste of materials as areas of maximum sagging will be not also be subjected to the maximum hogging. A more efficient solution is illustrated in figure 7. Here the depths of the sections differ along the length of the bridge

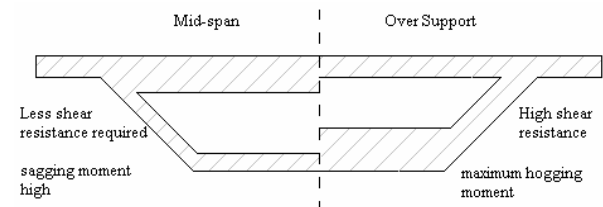


Figure 7: Efficient use of differing cross-sections

depending on the forces that they will be subjected to. At the mid-section where the sagging moments will be dominant the top flange will have a greater depth. The shear forces at this point will be low and so the width of the webs need only be small. Over the supports the section will feel the opposite loads and so here the section will have a deep bottom flange and much thicker flanges. This process would be far more costly due to the additional work required in forming the sections. However, the savings in materials and the improved sustainability of structure make this an extremely viable option.

3.2 Approach Spans

The structure of the approach spans is formed in much the same way as with the main span with preformed concrete box-sections held together using post-tensioning cables. However, rather than having one continuous section, the deck is split in two supported by two piers as illustrated in figure 7. Once again these sections suffer from the same inefficiencies as the sections used for the main span and so their structural performance could also be greatly improved with careful design.



Figure 7: Cross-section of pre-cast concrete sections for approach spans.

3.3 Cable Stays

The cable-stays that connect the deck to the pylons are arranged in a single plane with 21 cables spanning out from each pylon. Each stay is formed using bundles of high-tension steel cables that have been spun together. The largest stay consists of 82 strands and weighs approximately 37-tons. These are then sheathed using steel tubing to provide protection from corrosion in the harsh marine environment. The stays are bolted to the desk segments through anchorages that are embedded below the road level. They then pass up through the central pylon and back into the corresponding section on the opposite site. This creates a symmetrical system that balances the loads and reduces the bending moments induced in the pylon.

3.3.1 Simple Cable Force Calculation

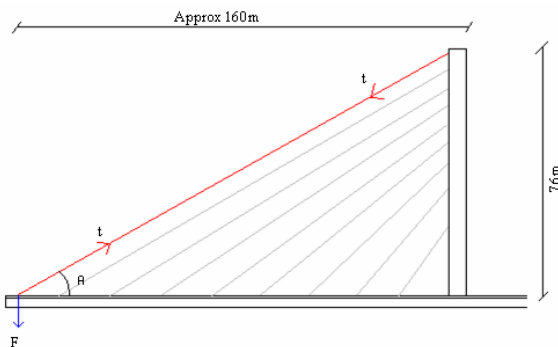


Figure 8: Dimensions of longest stay for calculation of tension, t .

Each cable supports two of the pre-cast concrete segments, each weighing approximately 200t. This is equivalent to a 4000kN of unfactored vertical load represented by F . (The live load will be small in comparison and so will be negated in this instance). The cable angle, θ can be calculated using:

$$\theta = \tan^{-1} 76/160 \approx 25^\circ.$$

Therefore:

$$t_{\text{factored}} = F \times 1.4 / \sin \alpha .$$

$$t_{\text{factored}} = 5600 / \sin 25 = 13250kN.$$

Where 1.4 is the factor of safety for dead loads when using steel. This tension force will induce an axial force in the bridge deck due to its horizontal component putting it into compression:

$$N = F \times 1.4 / \cos \alpha .$$

$$N = 5600 / \cos 25 = 6170kN.$$

Choose to use high tensile steel tendons with a yield strength of 1650N/mm². Therefore the area of steel required will be:

$$A_s = 13250000 / 1650 = 8000mm^2 .$$

Therefore the diameter of cable required will be around 100mm. In reality the cables are roughly double this value. This disparity is not surprising due to the assumptions made in the hand calcs above. This same process can be repeated for each of the stays to give estimates of the total forces in the structure.

Most conventional cable-stayed bridges consist of two planes of cables running along either side of the deck. This provides two planes of fixity thus giving the bridge resistance to torsional effects. By removing one of these planes we also remove the structures ability to resist torsion. Instead this has to be provided by substantially stiffening the deck. This could have required an increase in the depth of the deck, leaving it out of proportion. However, this ill effect has been avoided due to the large number stays and the introduction of stiffeners within the box-sections. Therefore the overall aesthetic has not been compromised. An alternative solution to this problem could have been provided by using an a-frame system such as the one seen in fig 9. Here the cables all span



Figure 9: A-frame solution to torsion problem

from the vertical section of the pylon and so the arrangement of the cables is retained as a single plane of. However, the inclusion of a closed triangular section formed by the a-frame gives the structure added stiffness.

3.4 Protective ‘Dolphins’

Due to the disastrous history of the original Sunshine Skyway, safety was paramount in the design of its replacement. One of the most obvious precautions taken as illustrated by fig.10 is the inclusion of 36 large concrete bumpers called *dolphins* that surround the piers close to the shipping lane which are at the greatest risk from passing ships. Each of these *dolphins* is designed to withstand the direct impact of an 87,000-ton ship traveling at a speed of 10knotts. This is far greater than that of the *Summit Venture* which caused the original collapse. The cable-stayed span provides a shipping lane that is more than double that of the previous bridge,

making it the perfect solution for preventing a similar tragedy.



Figure 10: View of the protective concrete dolphins surrounding the bridge.

4 Construction

Because this bridge consists of different structural systems the construction process was made more complicated than usual with multiple methods of construction being used in unison in order to produce the end result. Because of the bridges location surrounded by water it would not have been possible to use temporary propping which is considered to be the simplest form of



Figure 11: Concrete segments on large cranes had to be used into position.

4.1 Piers and Pylons.

The first stage of construction involved the erection of each of the piers. This process started 10m below the level of the water where large heavily reinforced concrete footings were constructed to form a solid base for the

huge structure to sit on. For the main pylons the structure was then built up by casting in-situ reinforced concrete segments using temporary form work. For the rest of the piers that support the approach spans, preformed concrete sections were transported to site on barges to be lifted into position by crane boats. Fig 11 shows this process in action. External post-tension cables were then added to the interior of these hollow sections which were tightened using jacks to put the whole structure under compression.

4.2 Approach Spans

In order to construct the two parallel roadways that approach the main span of the bridge an overhead launching girder was used. This is probably the most common method of pre-cast concrete construction. It involves the use of a truss-girder that spans between two of the piers, the role of which is two-fold. Firstly, it is used to winch up pre-cast segments into their approximate position from transport barges below. Secondly, it provides temporary support to those sections already in place whilst the rest of the span is being completed. Temporary stress bars are put in place to tighten the structure up into the correct position, and an epoxy glue is added to the joints to act as both a lubricant and a sealant. Once the entire span is in place, permanent pre-stressing cables are threaded through ducts left in the concrete and are tightened using hydraulic jacks. When at the correct tension they are anchored off and grouted giving the structure its full strength. The temporary supports can then be removed and the girder can be launched out across to the next span. Fig 12 gives an interpretation of the plant involved in this process. Due to the mammoth scale of this whole operation safety is of the utmost importance at all times, because any mistake could easily

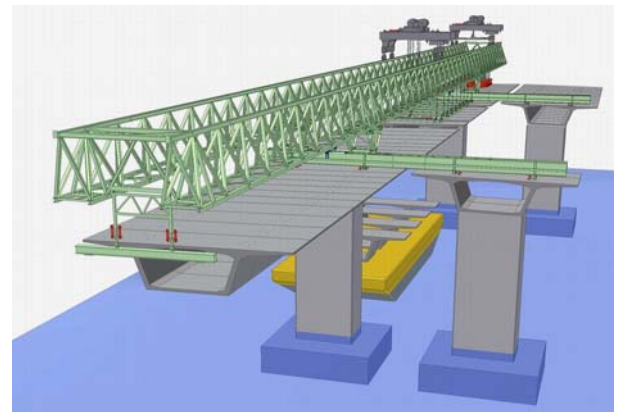


Figure 12: Arrangement of the Launching Girder

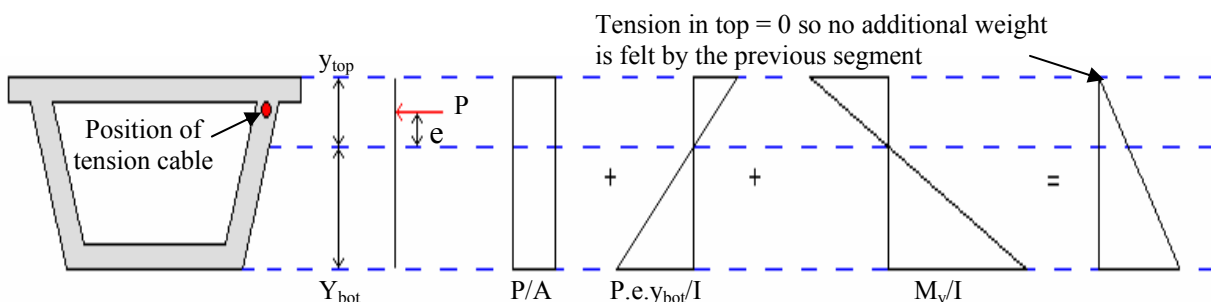


Figure 13: Demonstration of the use of pre-stress during construction

result in serious injury or even death. There are limitations to the spans that this technique can achieve due to the shear size and weight of the launch girder that is required. Beyond a certain length it is no longer an economical solution.

4.3 Main Cable Stayed Span.

Because of the much longer spans involved with this section of the bridge it was not possible to continue with the launching girder method at this stage of construction. Instead the construction team opted for a balanced cantilever approach. This involves building outwards from each of the two pylons in a symmetrical manor so that balanced is maintained about the sub-structure. Figure 14 gives two perspectives of this process. A mobile lifting platform sits at the edge of each cantilever in order lift the

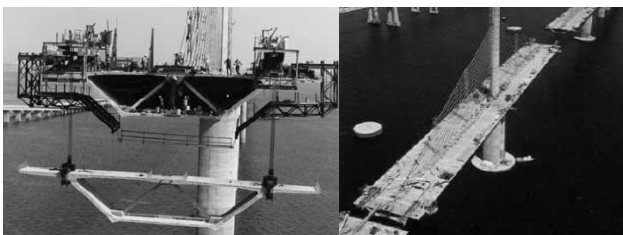


Figure 14: Lifting of pre-cast concrete section for main span (left) and view of the double cantilever construction nearing completion (right).

concrete segments into place. As each additional segment is added pre-stress is also added through internal cables in order to support the weight. This is a vital part of the process. Figure 13 shows how the pre-stress, P acting at an eccentricity, e from the centroidal-axis, CA is added to perfectly counteract the self weight of the segment so that no tension is transferred into the previous segments. Temporary cable-stay towers are often used during construction in order to provide further support as the cantilevers span further out. This greatly reduces the hogging moment felt over the piers and so reduces the need for increases on the deck thickness in these areas. As a result of this cable-stayed bridges lend themselves extremely well to this form of construction. This is because the presence of permanent supporting towers means there is no need for temporary works leading to a particularly cost-effective solution. The final stage of this construction process involves the joining of the two halves of the cantilevers. Rather than using a pre-formed this last section is cast in-situ in order to prevent any issues due to lack of fit is. For this project a large section was left out at the centre of the span and formwork

supported by gantries on either side was used to cast the final piece of the puzzle as shown in figure 15. Ducts were cast into the section so that tensioning cables could be added once the concrete had gone off. This however, is not really the best way to finish off a bridge like this due to the large amounts of form work required. Instead it would have been better to have left a far smaller gap so that there is no need for expensive gantries to support the casting.

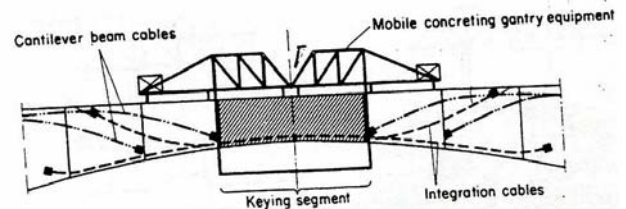


Figure 15: Large segment is left out. Formwork used from either end to cast the final piece.

5 Loading

Because this bridge was designed and built in America, it will not have been analysed using the same structural codes that we are used to. Therefore the loadings that were used are likely to differ to those that would be used in a similar British design.

5.1 Traffic Loading

The Sunshine Skyway Bridge carries four lanes of traffic and handles around 20,000 vehicles each day. Both the north and south bound carriageways have a width of around 12m. If a study of the traffic loads were undertaken using the British standards this large width would give rise to four 'notional lanes' of traffic as apposed to the two marked lanes. This is typical of American roadways due larger sizes of vehicles and general culture of the country. Each of these lanes would then be subjected to differing levels of both HA and HB loadings in order to find the worst possible case. Traffic can also have various secondary affects on the loading of the bridge. These can come in the form of longitudinal loadings for vehicular braking as well as from horizontal loads due to accidental skidding. A key consideration in the design for traffic loading is to insure that the crash barriers are able to withstand the impact of a crashing lorry in order to prevent the loss of life. Unlike with the majority of British bridges, the barriers that form the

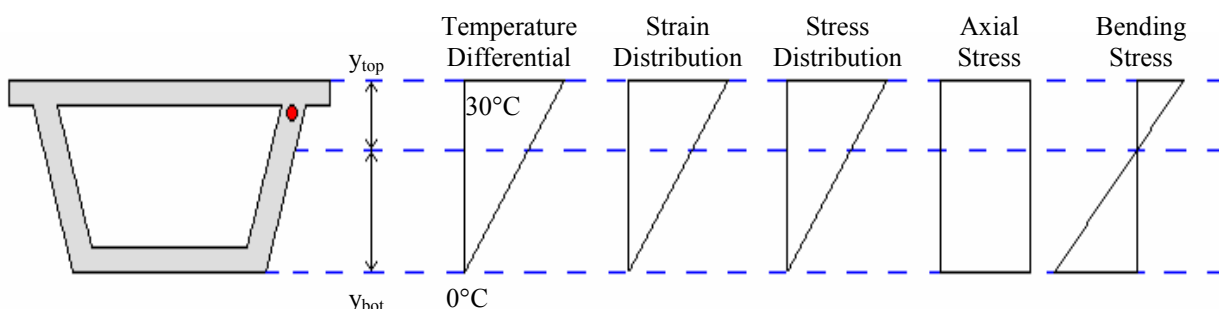


Figure 16: Stress and Strain distributions caused by variation in surface temperatures

parapets of Sunshine Skyway consist of large, solid concrete blocks that aim to resist such impacts rather than stopping them elastically.

5.2 Wind

The Sunshine Skyway Bridge is located in region of the world that frequently experiences hurricane strength winds. Consequently, it was important during the design stage to insure that the structure would be able to cope with such conditions without compromising its safety both during and after its construction.

In order to determine the wind characteristics during a hurricane a ‘Monte Carlo Simulation’ was carried out. This is defined as being *a probabilistic model involving an element of chance* [4]. This involves the use of computational algorithms to simulate events when it is not feasible to carry out actual experiments. The drawback of using this method without the aid of real-data for comparisons is that the element of chance leaves room for inaccuracies. The average hourly wind speed for a hurricane with a hundred year return period was estimated to be 105mph [5]. This then allowed for wind tunnel testing to be carried out on a 1:375 scale model of the bridge to ascertain the structural response when under both turbulent and calm flow conditions. From this estimates of the behaviour of the actual bridge could be made and checked against allowable values.

Each of the main piers that support the road deck across the main span have an elliptical profile which improve their performance under extreme wind conditions. The same cannot be said however, to the two pylons that support the cable stays. These both have much squarer profiles in plan and as a result are far less efficient. This is shown by looking at the Drag Coefficient (C_D) values as given in BS5400. With a height/breadth ratio of around 20 a square pylon will have a C_D of 1.8 whereas for a curved pylon it will be just 0.6. This means that the maximum wind gust (v_c) experienced by the pylon would be reduced by a factor of three which would be extremely beneficial.

5.3 Temperature

There are two possible temperature effects that can occur in bridge engineering and each can induce huge forces within the structure. This is especially true in the semi-tropical climate of the Tampa-Bay region where temperatures of 40°C are a regular occurrence. The first mode of effect occurs due variations in the effective temperature of the whole bridge. During the summer months the bridge will be subjected to far higher temperatures than during the winter months (the same can be said to a lesser extent between night and day). Consequently the bridge will have a propensity to expand and contract as the temperature varies. The second form of temperature effect that may occur may arise from variations in temperature between different areas of the structure. For example during the peak summer months ambient temperatures of 40°C combined with direct sunlight may see temperature of the deck surface reaching as much as 30°C above the datum temperatures, where as

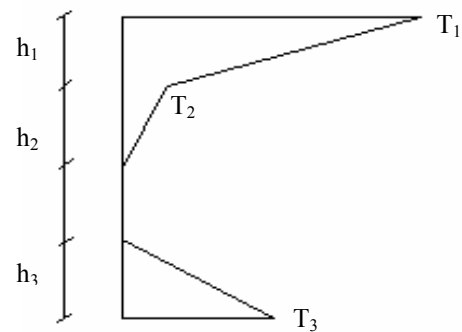
Adam T Sayers – ats21@bath.ac.uk

the underside of the deck that is cooled by the water below and kept in shade will be at a far lower temperature.

5.3.1 Exemplification

Figure 16 shows a representation of the stress and strain profiles that may arise from the scenario mentioned above, assuming a temperature distribution ranging from 0-30°C from the base to the top of the section and that any expansion joint have been blocked.

The temperature distribution through the section has been simplified from the standard distribution for concrete sections as shown below:



This was necessary because the non-uniform temperature distribution gives rise to non-planar stresses and strains making the calculations of forces and bending moments impossible.

The strain, ε can be calculated using equation (1):

$$\varepsilon = \Delta T \cdot \alpha . \quad (1)$$

Where ΔT is the temperature differential and α is the thermal coefficient of expansion, which for concrete is equal to $12 \times 10^{-6}/^\circ\text{C}$. Therefore:

$$\varepsilon = 3.6 \times 10^{-4} .$$

Equation (2) can then be used to calculate the maximum stress, σ_{\max} .

$$\sigma_{\max} = \varepsilon_{\max} \cdot E . \quad (2)$$

Where E is the young's modulus of the material which is around 30GPa for concrete. Therefore:

$$\sigma_{\max} = 10.8 \text{MPa} .$$

If we assume the CA is 3m up from the base of the section, we can calculate the total σ_{axial} as the σ_{moment} is 0 about this point. Therefore:

$$\sigma_{axial} = (10.8 \times 3) / 4 = 7.5 \text{MPa} . \quad (3)$$

Along the bottom flange σ_{axial} will be equal to σ_{moment} now that we have these values we can ascertain the values of the Axial force, N and the Moment, M that have been

induced in the structure from the following two equations respectively:

$$N = \sigma_{axial} \cdot A. \quad (4)$$

$$M_{bottom} = (\sigma_{axial} \cdot I) / y_{bottom}. \quad (5)$$

To approximate the cross sectional area and second moment of area, a simplified square box-section was used with an estimated thickness of 200mm of both the flanges and the webs. This gave the values of 9.36m² and 35.5×10m⁴ respectively. Therefore the final values for the temperature effects on the bridge are:

$$N = 70.2MN.$$

$$M_{bottom} = 89MNm.$$

Although only rough estimates this example clearly demonstrates how large the effects that temperature can have on a structure can be. These values should be combined with other load types to ascertain the worst possible case.

If the bridge is a rigid structure the movements brought on by the effects of temperature may induce huge bending moments throughout and could even lead to collapse. Certain attempts have been made with the design of this bridge to try to mitigate these ill effects. Firstly four expansion joints have been included along the length of the bridge deck. The arrangement of the fingers as shown in fig 17, allows the bridge to expand and contract by quite large amounts whilst still allowing traffic to flow

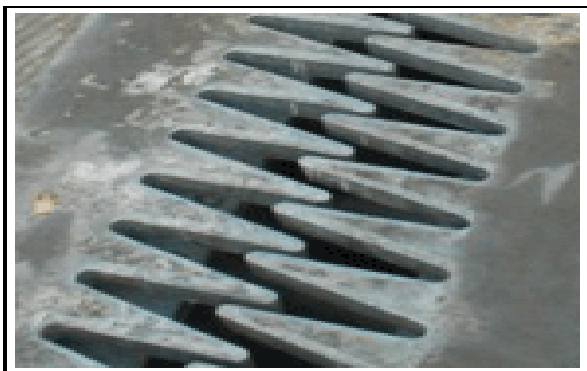


Figure 17: Example of the type of expansion joint used in this bridge

over them. This prevents the build up of stresses within the structure. One draw back of such a joint is that any differential vertical movements may cause the fingers to splay upwards risking damage to the tyres of passing vehicles. A second disadvantage to the use of expansion joints is that they require careful maintenance in order to insure they are kept free from any blockages. If they do become blocked they are rendered useless.

The deck of the bridge is given greater flexibility by the addition of Teflon bearings at the tops of each of the piers on which to sit on. These consist of a chrome dish with a slippery Teflon surface that accommodates for both rocking and slight sliding motions. These days this type of

bearing has been out-dated due the advent of ‘rubber pot’ bearings. These perform just as well as Teflon bearings in terms of flexibility but for a fraction of the cost. Therefore it would make sense to install them the next time the bearing need to be replaced.

The final design feature of this bridge that helps it to perform well under the effects of temperature is the clever design of the two central piers that support the cable-stay pylons. Although being very deep in plan their profile has been greatly reduced by forming them from two separate sections as apposed to just one much thicker one as demonstrated by fig 18. This allows them to be very stiff in bending whilst still being flexible in terms of lateral movements thus alleviating the stresses that would have otherwise built up.



Figure 18: A clear view of the use of twin slender piers to add flexibility.

6 Durability and Serviceability

One of the biggest problems that Sunshine Skyway faces is the harsh marine environment in which it is located. The high salinity levels in the air coupled with the extreme humidity levels of the tropical climate make for a highly destructive concoction that is constantly attacking the structural integrity of the bridge.

Probably the most susceptible of the structural elements are the steel cable-stays. The air conditions dramatically increases the rate at which the corrosion of steel takes place, and as a thin coating of protective paint is all that stands between the steel and the aggressive environment and so the stays are at great risk. Any chips in the paint work would result in rapid rusting. Therefore, the maintenance of the stays is of the utmost importance with continual checks and repairs being carried out to insure their protection. One solution that would give the cables a greater degree of protection would be to apply a secondary protective barrier around them that forms an air tight seal. An example of such a product, called ‘Cableguard™’ uses a laminated plastic wrap to form a weather-proof seal around the cables. This can be made to be any colour you choose and its application is subtle so to reduce any negative visual impacts this material may have.

The pre-tensioning (PT) cables that hold the structure together have proved to be susceptible to the effects of this harsh environment. The cables that sit within the piers of the bridge are situated externally within the hollows of each of the section and as a result are not protected by a concrete cover. Visual inspections have shown that a high level of corrosion has taken place, and in many instances failures of individual cable strands have begun to occur compromising overall strength of the cables. The severity of the damage can clearly be seen in fig 19.

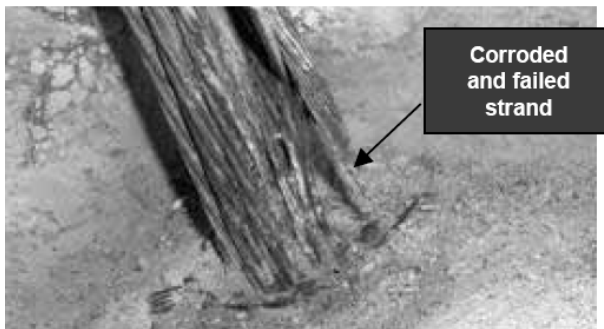


Figure 19: Results of a visual PT inspection in one of the piers

Extensive testing has been carried out as a result of these findings in order to ascertain the extent of the damage. As well as visual inspections other passive methods have been used to help with these inspections such as vibration tests [1]. Luckily because the cables are not embedded within the concrete repairs can be carried out reasonably easily, either by replacing individual strands and re-tensioning or by strengthening the system through the use of composite materials. Inspections are also carried out on the internal PT cables within the concrete of the deck. Straightforward visual testing is not possible as the cables are entirely covered; therefore destructive forms of testing are required, where the concrete is broken away to reveal the state of the tendons below. In general the damage to cables in these areas is far less due to the added protection from the concrete.

Signs of fatigue are beginning to show in other areas of the structure. For example cracks are beginning to form

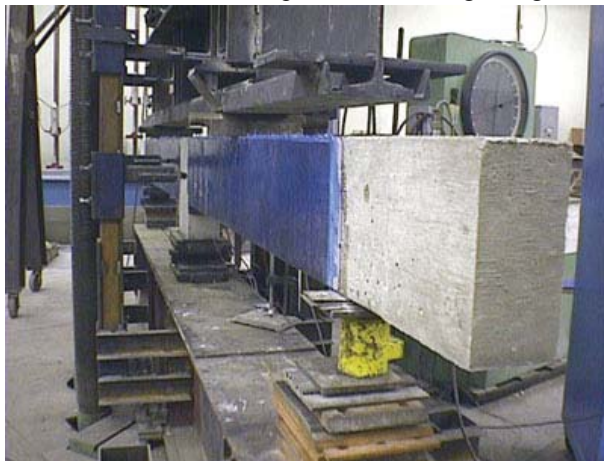


Figure 20: Concrete beam coated in FRP wrap undergoing strength testing under laboratory conditions

in the concrete in the lower areas of the bridge. This suggests either a slackening off of the PT cables causing areas of concrete to go into tension, or excessive deflections of the members. Attention needs to be paid to this in order to prevent such damage from propagating further. A new technology that is being developed to aid in the repair of such deterioration involves the use of composites wraps. These are known as externally bonded fiber reinforced plastics (FRP) [7] and are the equivalent of bandages for the structural world, an example of which can be seen in figure 20. They are wrapped around the structure to provide additional strength and bonding. This is an attractive option to many as it is quick and easy to install and is also sympathetic to the look of the structure.

7 Future Improvements and Expansion

The simplest way to expand this bridge would be to make more efficient use of the extremely wide carriageways by creating an additional lane in the space already available. If this bridge was in the UK this is a likely situation and it is one that is often used on roads throughout the country. However, it is a cultural trait of Americas that ‘big equals best’, and so public opinion is not likely to react well to such a move. Also HGVs tend to be of a much greater size in the US and so this idea may not even be practical. Therefore it seems like a poor choice for the future.

Another method that could be used to extend this bridge could be through the construction of a twin bridge running parallel to the original. This would be fitting in an historical sense because the original steel cantilever version of the bridge built in the 50’s had an identical sister that has since been destroyed to make way for the new bridge. The twin spans can be seen in fig 21. Despite this historical link the construction of a second bridge



Figure 21: The twin spans of the original Sunshine Skyway

would be an absolute travesty as it would entirely undermine some of the key ideals of the design. The use of a single plane of cables was specifically chosen for its elegant and ordered appearance despite compromising on the structural efficiency of the bridge. By adding a second bridge there would be no way of avoiding the crisscrossing effect between the stays which is the downfall of many cable-stayed bridges. Also the character

and boldness of the design may feel somewhat diminished due to the loss of individuality. There is no way that this could be a viable option as it risks transforming one of the most beautiful bridges in the world into an eyesore.

A final way of trying to extend the capacity of the bridge would be through the widening of the actual road deck itself. If the designers had decided on the approach described earlier in fig 9 it would be virtually impossible to achieve this due to the position of the pylons. Therefore, although it performs more efficiently as a structure, it may be considered as a somewhat short-sighted resolution. The structure as it stands however, with single pylons in the centre of the deck is perfectly suited to such an extension. In order to attach the new sections onto the existing deck pre-tensioning cables could be used in a similar way to those used during balanced cantilever construction. This process would be made easier by leaving empty ducts within the pre-existing deck sections ready to receive the additional cables. Before such an extension can be carried out, careful studies need to be made to establish the extra loads that the bridge will be subjected to from the increased usage. The ability of the bridge to support these loads is critical. If it is found that it is not possible under current conditions, it would be feasible to retrofit the members in order to give them the necessary strength required.

Summary

The overall feel of this bridge is one of simplistic beauty, and it has proved to be a triumph in nearly all aspects of engineering design. As a result of this it imparts

a great sense of national pride earning its role as the 'flag bridge' for the state of Florida.

Acknowledgments

The template of this report is based upon the work of Professor Tim Ibell of the University of Bath who also helped to provide much of the background information on bridge design. A special thanks should be given to Ian Molesworth for giving up his time to help make this conference possible.

References

- [1] Garcia, J. *The Skyway Bridge - Yesterday, Today & Tomorrow*.
- [2] Goldberger, P. October 16, 1988, *New York Times*.
- [3] Gauvreau, P. University of Toronto, Canada. *The Three Myths of Bridge Aesthetics*.
- [4] Dr. Shiflet, A.B. 2002 *Scientific Programming - Monte Carlo Simulation*.
- [5] Davenport A.G. The University of Western Ontario *Sunshine Skyway Wind Tunnel Study*.
- [6] www.dsbrown.com/.../cableguard/cableguard.html
Cableguard™ elastomeric wrap
- [7] Nanni, A., Bakis, C.E. *Externally Bonded FRP Composites for Repair of Reinforced Concrete*- The Pennsylvania State University