A CRITICAL ANALYSIS OF SANTIAGO CALATRAVA’S TURTLE BAY SUNDIAL BRIDGE

R. E. Mort

Undergraduate Student, University Of Bath, Bath, Bath and North East Somerset, England

Abstract: This paper is a monograph of the Sundial Bridge Redding California that epitomizes Santiago Calatrava’s approach to the aesthetic design, structure and construction of the United States first steel inclined pylon cable stayed bridge. The examination of this unusual pedestrian walkway spanning over the Sacramento River includes Calatrava’s design precedents and how innovative technology achieved meaningful and pleasing results. This document contains analysis of aesthetics, structural design, foundation geotechnics, temperature effects, loading simulation, construction techniques and an overall conclusion of one of Santiago Calatrava’s infamous cantilever spar cable stayed bridges.

Keywords: Sundial, Calatrava, Redding, Inclined Pylon, Cantilever Spar Cable Stay.

1 Introduction

Redding, California is an acquaint city of population 87,000 and is the largest city North of the Sacramento River. In the early 1990’s Redding began to see a decline within the Cascade Mountain pine forestry industry and as an outcome the city began to enter a spiral of depression. In an attempt to revitalise the city and become a tourist attraction, Redding embarked on redevelopment of its infrastructure commissioning many new builds such as the sport’s park, aquatic centre, public library, theatre and the star attraction a footbridge.

A very modest bridge proposal was put forward spanning the Sacramento River connecting trails with the Turtle Bay Exploration Park but this was rejected when the McConnell Foundation offered to pay for a signature bridge. At this point the ‘starchitect’ Calatrava was approached tentatively, assuming that perhaps such a small culturally void city would obtain the helping hand of such a prestigious designer. To very ones disbelief Calatrava accepted.

On several visits to the site and many technical sketches later the design of the Turtle Bay Pedestrian Bridge was completed although this design created a detailing, fabrication and erection nightmare. This was due to Calatrava only producing renders of the bridge leaving the engineering detail to other parties. The structure opened on July 4th 2004, two years behind schedule with an astronomical price tag of $23.5 million [1] after every aspect of the structure rose significantly. This ended in the McConnell Foundation paying $15.5 million [1] with the rest coming from the tax payer.

Mr Robert Edward Mort – rem24@bath.ac.uk

2 Final Design

The final design resulted in the bridge being 213m in length having an iconic feature of an inclined tapered pylon with 14 cables, connecting to one side of a truss deck supporting the 128m truss span over the Sacramento River. This phallic symbol rises 66m at an angle of 42° [1] serving not only as a substantial structural part of the bridge but also as the world’s largest gnomon casting shadows upon a plaza North of the bridge. The pylon has no backstays due to its self reliance upon its own dead weight to counter act forces exerted by the deck. This prevents any moments from being generated at the pylons base and so only allows vertical forces to be transferred to the bedrock beneath. The West face of the pylon also supports the bridge’s triangular deck due to its moment attachment.

The decks structure consists of a triangular pipe truss system with varying sized chords. The truss is asymmetrical in cross section allowing the centroid of the truss to become closer to the pylon allowing a smaller cantilever distance for the pylon to cable connections. This superstructure supports an aqua green translucent glass deck with a non skid surface containing strips of granite and more than 60,000 pieces of white imported Spanish tile [2].

Along the total 213m length of the structure the truss system is supported at 3 points. The deck is supported by an asymmetric connection to the tower for the first span while the second span (128m main span) is supported by the 14 galvanised steel cables and then on the South riverbank the third span is supported by steel stanchions. The overall outcome is a bridge that resembles key aspects of Calatrava’s Alamillo Bridge in Seville but with many major differences. The end result
is a flashy landmark structure that seems to have improved the image of Redding city while enabling a pedestrian crossing of the Sacramento River.

**Figure 1:** Final design of the Sundial Bridge

### 3 Aesthetics

The aesthetical analysis of the Sundial Bridge follows from the principle 10 rules.

This unique shape created by the asymmetric inclined tower and the light weight bridge deck creates a logic defying structural system whereby a mutual dependency is created as seemingly the pylon nor the deck could stand alone without the other. This can be perceived by the user as a certain amount of instability within the bridge as its workings are predominately under ground contained within the foundations of the structure. It could be assumed that the visual image of this bridge may cause users to feel uneasy as this is an extraordinary piece of infrastructure which has no correspondence with traditional suspension or arched bridges and so stirs emotional senses when one tries actually using the bridge.

The functionality of a bridge is dependant on its structural hierarchy and due to the Sundial Bridges skeletal form having neither skin nor absolutely enclosed spaces to hide its structural system this bridge displays architectural sensitivity unlike the majority of other bridges. From elevation the bridge is striking due to its unusual asymmetry but this view is rarely attained so Calatrava provides a drawing cross section dragging the user over its body. This is obtained through a single mono line of equally spaced cables attached to the bridge deck creating a major and minor pathway over the bridge. With the cables being positioned on the deck uninterrupted sight is obtained of the placid landscape of Turtle Bay Exploration Park when using the bridge.

This green bridge has juxtaposing portions having a light weight deck with a visually heavy pylon. The bridge seems to hover over the Sacramento River without touching the water resting on the well defined river banks while boats pass beneath as they fish for salmon, steel head and rainbow trout. The excess engineering of the Sundial Bridge reflects a deliberate choice to produce monumental architecture rather than an inconspicuous river crossing. The intended bold confidence of the immense tower overshadows the smooth, translucent, fragile decking attracting curiosity and even anxiety in the spectator.

**Figure 2:** Major and minor pathway on the deck

The Sundial Bridge links sculpture with architecture giving form and shape to its tactile materials. The sculptural form of the bridge (bird in flight) \[2\] shows the simplicity of the structure while giving order to its parts. The design of the single span cable stay arrangement with equal spacing’s allows a harp shape form to occur preventing any criss crossing of cables when viewing from an angled position. This creates a more aesthetically pleasing bridge and when viewed from afar the cables disappear allowing a clean view of its major structural parts revealing the true simplicity of its form.

**Figure 3:** Sundial Bridge during daylight

With many tourists visiting Turtle Bay daily, seeing and using the bridge, the particular form of every element and detail had to be designed with the same attention as the larger iconic bridge sculptured pieces. The bridge deck comprises of translucent structural glass which is illuminated from below with 210 lights \[3\] providing an aquamarine glow during evening hours. This prevents any interference/competition within the vertical plane of the bridge between high raised lamps and the inclined pylon. The panels used to surface the bridge minimize shadows that could agitate the waters temperature during fish spawning seasons preventing disturbance to the endangered Chinook salmon population. This glass also treats the user by creating a lighter than air experience during passage. Other fittings such as handrails along the length of the bridge are inclined toward the deck, each individually representing the pylon, continuing the dominant effect of this sculptural part on the structure.

The superstructure of the bridge is painted white denying individual materialization of specific elements therefore unifying the different materials giving purity to the bridge. This white figure then stands apart from
the cloudless sky of Redding allowing an unhindered view of the structural integrity of the bridge by pronouncing the 14 cable stays and the truss deck. All steel elements have 3 coat paint systems with a white epoxy finish [4].

The Sundial Bridge was commissioned to stimulate Redding’s failing economy through increased tourism to the region. This centrepiece connects the North and South campuses of Turtle Bay Exploration Park while also serving as a connection to the Sacramento River Trail system. While everyone in Redding is fond of this focal point the cost of the structure rose continually throughout its design and construction phases. This resulted in the privately commissioned build to need $8 million of public funding [1]. Many believe this was a small price to pay to reinvent a city in a spiral of decline.

Clearly while this bridge is structurally very complex it can be considered to have reams of character even though it is not a truly unique design (Puente Del Alamillo, Seville). This is the first steel inclined pylon cable stayed bridge in the United States, with challenging asymmetry, an unbelievable camber complexity and also with a major structural component converted to a working sundial; this bridge must have a distinctive edge over its conventional counterparts. It can be seen that this very complex structure does not appear in any way chaotic and this is a tribute to Calatrava allowing a strenuous engineering feat appear with a simplistic appearance. The outcome is a bridge with character like no other, continually making the user question how it actually stands in such a slender form.

Inspirations for this design where obviously influenced by Puente Del Alamillo in Seville with the flying bird and the skeletal form of his once pet dog being at the forefront of his ideas, but also many other minor influences were involved such as his office furniture and also the presence of a phallic symbol. Nature is believed to have some of the most functionally efficient forms and so Calatrava uses this to produce magnificent works of art from everyday sights and experiences. The truss bridge deck can be assumed to have been inspired by the form of a skeleton while the pylon was inspired from office light fittings and furniture which is used to represent the male organ.

Calatrava has successfully fulfilled each of Fritz Leonhardt’s rules for the analysis of the aesthetics of a bridge producing a world icon that some say has not been bettered even though the structure is neither efficient nor sustainable as well as having a gargantuan price tag of $23.5 million.

### 4 Structural Designs

The cable stays holding the truss bridge deck above the Sacramento River resolve into horizontal forces acting at the top of the pylon. Calatrava’s ingenious idea was to use the pylon as a huge cantilever producing a huge moment at its base counteracting moments caused by the deck dead weight. To prevent the pylon from failing vast quantities of concrete and steel was needed to resist these moments at the base during construction when the deck was not present.

The simplest solution for this situation would have been to tie back the pylon with backstays balancing the cable stays attached to the bridge deck. No moment is then induced at the base of the pylon and a smaller foundation system can be applied along with a simpler tower design.

The final design resulted in a pedestrian bridge deck suspended by stainless steel cables from a pylon leaning back toward the riverbank using its dead weight to balance the tension in the cables and reducing the overall moment at the pylons base. The single inclined tapered pylon inclined at 42º creates an obvious visual harmonious tension between the pylon and the deck through the steel cables.

**Figure 5:** Forces and moments applied to the bridge

The pylon is 66m high and runs in the North South direction having a base 34m by 23m with a 36º angle between East and West walls [4]. The cable stays are connected to the pylon by cantilevered plate brackets on the West face of the tower [1].

Large bending moments are induced in the deck at the connection point with the pylon and also in the pylon because of the lack of backstays. To withstand these moments large quantities of material are needed and this is ironic as the structure appears to be very light. The pylon could have had its mass significantly reduced if backstays were incorporated into the design.

As the deck is permanently attached to the inclined pylon at its base the appearance is given that the cables are not truly needed as the truss decking looks ample to span the river. This in reality is true although they are essential for preventing deflection within the deck. It is said that there is a 3m maximum dead load deflection [1] when the cables are not present and by changing the truss form at all does still not allow the decking to span the full 128m of river so the cables are required with the presence of the inclined pylon at all times.

The Sundial Bridge deck system is a triangular pipe truss with varying diameter chords. The lower chord is 360mm [4] in diameter while the two top chords are 280mm in diameter. The truss is asymmetrical having...
the bottom 360 mm chords closer to the pylon allowing the centroid of the truss to have a smaller cantilever distance for the pylon cable connections. This had repercussions due to the structures asymmetry making the deck require horizontal, vertical and longitudinal cambering. The cables attaching the deck to the pylon are connected to the deck through transverse bulkheads in the truss [1].

![Figure 6: The steel truss deck](image)

The overall outcome for the Sundial Bridge is a structure consisting of an angled cantilever pylon, loaded by cable stays on one side only. This results in the pylon resisting bending and torsional forces while the foundation prevents overturning. Combining these two structural types in one design means that the bridges structure is less efficient but visually pleasing.

5 Loads

The Sundial Bridge is dominantly used for pedestrians and cyclists and thus has considerably lighter loadings than highway bridges. As there are no barriers at either end of the deck this bridge is designed to support accidental vehicle loading in any unforeseen circumstance. The imposed loads result from pedestrian and cycle traffic along with minor common construction and maintenance loads e.g. service vehicles and accidental situations. These loads result in vertical, horizontal, static and dynamic forces.

There is 4 level structural hierarchy in the Sundial Bridge starting from the live loads being applied to the deck and then transferred to the cables and then to the pylon and finally to the foundation.

This paper uses BS 5400-2:2006 and BS EN 1991-2:2003 to study the loadings on the Sundial Bridge.

5.1 Dead and Superimposed Dead Loads

The dead loads of the Sundial Bridge are approximately 37MN for the incline pylon and 16MN [5] for the truss deck. The 14 cables from the pylon are angled at 30° to the horizontal and they are post tensioned Eq.(1) to carry the weight of the truss deck.

\[
\cos 30 = \frac{64 + 73}{T}
\]

\[
Total \ T = 158MN \approx 160MN
\]

5.2 Nominal Pedestrian Live Loading

The loads due to cycle traffic are generally much lower than those due to pedestrian traffic and so the nominal pedestrian live loading Eq.(3) on the supporting elements of the Sundial Bridge are:

- Main Span > 36m 128m > 36m
- The loaded length is in excess of 36m.

\[
K = \frac{(HA \times 10)}{(L + 270)} = \frac{(22.1 \times 10)}{(128 + 270)} = 0.56 \quad (2)
\]

Uniformly distributed live load:

\[
 udl = K \times 5 = 0.56 \times 5 = 2.8kN / \text{m}^2 \quad (3)
\]

As the Sundial Bridge has a width of 7m the width exceeding 2m can have its load intensity reduced by 15% on the first metre in excess of 2m Eq.(4) and any additional metre after 3m can be reduced by 30% Eq.(5). The intensities are then averaged and applied as a uniform intensity over the bridges full width.

\[
\text{After 2m:} \quad 0.85 \times 2.8 = 2.38kN / \text{m}^2 \quad (4)
\]

\[
\text{After 3m:} \quad 0.7 \times 2.8 = 1.96kN / \text{m}^2 \quad (5)
\]

Average intensity over full bridge width Eq.(6):

\[
(2 \times 2.8) + (1 \times 2.38) + (4 \times 1.96) \over 7 = 2.26kN / \text{m}^2 \quad (6)
\]

Load combination 1 Eqs.(7) \[ \gamma_{fl}: ULS=1.5 \quad SLS=1 \]

\[
uls = 1.5 \times 2.26 = 3.39kN / \text{m}^2 \quad (7)
\]

\[
sls = 1 \times 2.26 = 2.26kN / \text{m}^2
\]

Load combination 2 Eqs.(8) \[ \gamma_{fl}: ULS=1.25 \quad SLS=1 \]

\[
uls = 1.25 \times 2.26 = 2.83kN / \text{m}^2 \quad (8)
\]

\[
sls = 1 \times 2.26 = 2.26kN / \text{m}^2
\]

Special consideration is taken when the bridge is loaded along its full length where crowds may be expected.

5.3 Accidental Wheel Loading

As neither end of the bridge has effective barriers protecting itself from vehicular traffic, the bridge must be able to withstand local effects of nominal accidental wheel loading. Also this then allows the bridge to be used in the case of an emergency so that the ambulance or fire services can use the bridge. The wheel load arrangement is placed over a central point of 2.3m from west side of the deck and 106.5m along the deck creating the most adverse loading effects on the bridge.

Since the bridge is designed to support vehicle loading in either the case of an emergency or an accidental venture then 25 units of HB loading should be able to be withstood at any location on the bridge. 25
units equal 250 KN of load from the vehicle resulting in 62.5KN of vertical force generated by each wheel.
Combination 1 Eq.(9) \( \gamma_f: \text{ULS}=1.5 \quad \text{SLS}=1.2 \)
\[ uls = 1.5 \times 250 = 375kN \quad sls = 1.2 \times 250 = 300kN \] (9)

The nominal accidental wheel load is assumed to be uniformly distributed over a circular contact area assuming 1.1 N/mm².

5.4 Horizontal Forces

The largest horizontal vertical force Eq.(10) being endured by the bridge acts simultaneously with the corresponding vertical load of the accidental wheel loading and so is taken as 60% of total weight of service vehicle:
\[ H = 0.6 \times 375 = 225kN \] (10)

5.5 Live Load Combinations

If accidental wheel loading occurred on this footway it need not be considered in the load combinations 2, 3 of BS 5400-2:2006 and also no other primary live load needs to be considered over the bridge.

5.6 Horizontal Dynamic Loading

If crowds form on the bridge then consideration must be taken of horizontal dynamic loading; this is due to the horizontal natural frequency of the crowd possibly becoming less than 1.5Hz. This is taken into account later under the natural frequency section.

5.7 Piers and Impact Loading

As the Sundial Bridge stands over 4.5m away from any neighbouring road horizontal impact loading on bridge piers can be ignored.

5.8 Compression in the Deck

Compression is induced within the deck due to the 14 cable stays having a horizontal component force pulling the deck in the direction of the inclined pylon. The post tension force in the cables collectively is approximately 160 MN and so the largest compression force is C along the span Eq.(11) nearest to the pylon.
\[ \cos 30 = \frac{C}{160} \quad C = 139MN \] (11)

5.9 Parapet Loading

The pedestrian restraint system installed on the edge of the bridge has intervisibility preventing users from feeling contained whilst crossing the structure. As this bridge is used predominately for pedestrians and cyclists a normal duty class 3 system was installed. With cyclists using the bridge the restraint system height is 1200mm and this is above the 1150mm height required by the design standard BS 7818. The top edge of the parapet is designed to withstand a 1.4KN/m horizontal force. The posts (spacing’s 1.5m) and frame vertical members have a; nominal transverse load Eq.(12), nominal longitudinal load Eq.(13), transverse design live load Eq.(14) and a longitudinal design live load Eq.(15) as shown.

\[ 1.4 \times 1.5 = 2100N > 1000N \] (12)
\[ 700 \times 1.5 = 1050N > 1000N \] (13)
\[ 2100 \times 1.5 = 3150N \] (14)
\[ 1050 \times 1.5 = 1575N \] (15)

At any point below 1m of the parapet when the horizontal load equals the longitudinal member nominal live load for serviceability the deflection is 40mm.

The steel restraint arrangement is galvanized and painted with a 3 coat paint classification with the final coat being white epoxy. This ensures longevity to the system preventing any water traps from corroding the structure.

The foundation of the guardrail uses a base plate, fixing the restraint system to the main structure by stainless steel holding down bolts. This connection is designed to allow the guardrail to withstand loads 50% greater than the design load calculated above.

6 Bending Moments induced by UDL

It can be assumed that the max bending moment Eq.(16) induced in the deck due to pedestrian loading is:
\[ w = 3.39 \times 7 = 23.7kN/m \]
\[ M = \left( \frac{wL^2}{8} \right) = \left( \frac{0.24 \times 128^2}{8} \right) = 49MNm \] (16)

The uniform torque per unit load on the deck Eq.(17) occurs when the major pathway on the deck is fully loaded while the minor pathway is completely empty. The major pathway is 4.7m wide.
\[ \tau = 3.39 \times 4.7 \times 2.35 = 37.4kNm/m \] (17)

6.1 Bending

The Sundial Bridge has a total length of 213m with a main span of 128m. To calculate the maximum bending moment Eq.(18) within the deck the overall system must be simplified to a simply supported beam with a pin connection at the South side of the Sacramento River and a fixed connection at the North side (i.e. the inclined pylon). The cable stays which are positioned asymmetrically on the bridge can be assumed to relieve the dead load of the deck without inducing any moments. This will then only allow the bending moment caused by the live load to be considered. The length of the continuous beam is considered to be 128m in length as this is the largest free span. The largest bending moment will be created by the accidental vehicle loading at a position 64m away from the inclined pylon while pedestrian uniformly distributed live load 3.39KN/m² acts across the whole deck. The vehicle will induce a vertical load of 375KN as calculated earlier.
\[ M = \frac{\left( w \times 0.75L^2 \right)}{8} + \frac{\left( Pa^2b(2L+b) \right)}{2L^3} \]
\[ M = \frac{\left( 3.39 \times 7 \times 0.75 \times 128 \right)^2}{8} + \frac{\left( 375 \times 80^2 \times 48 \times (2 \times 128 + 48) \right)}{2 \times 128^3} \]
6.2 Torsion within the Deck

The 14 cable stays attached to the bridge deck are not centred on the walkway but instead dissect the bridge into a major and minor path. This 2/3 to 1/3 split when looking longitudinally over the deck creates torsional affects resulting in the bridge deck wanting to roll.

Figure 10: Torsion Diagram

To reduce these effects an asymmetrical truss system below the aqua marine translucent glass uses its varying length members to move the decks centre of gravity closer to the connection line of the cables. This reduces the cantilever arm [1] so that the point centre of gravity of the deck produces a smaller torsional effect. This torque in the deck is then carried along the truss to either side of the river bank onto the piers of the bridge.

The diagram below shows the torsional moment diagram caused by pedestrian loading on the 2/3 of the deck.

Figure 11: Torsional bending moment of deck

6.3 Buckling

The main span of the bridge truss deck over the Sacramento River with its 14 cables could potentially buckle under the constant compression force by these spar cables when the deck is fully loaded. The bridge would then fail by compression between each cable effectively crushing the deck due it not being able to withstand this horizontal force pulling the bridge back toward its inclined pylon.

6.4 Inclined Pylon

The pylon is 66m tall and is placed on the North South axis acting as a sundial casting its shadow on a plaza below. With the pylon having no backstays, to withstand some of the bridge decks loading the pylon is inclined at 42° to use its dead weight to equilibrate the moment induced on the pylon by the deck. Due to this lack of backstays the pylon has a foundation 14m deep to resist the bending forces allowing them to be transferred to the ground without causing overturning.

At the base of the structure it is 34m long by 23m wide with a 36° angle formed between the East and West walls [4]. The structure is furthermore complicated by all the interior walls of the pylon not being parallel to their exterior brothers. The complexity of this tower resulted in its fabrication becoming a nightmare after needing to have horizontal, vertical and skewed stiffeners [4] preventing itself from the effects of buckling. The end result is a unique pylon which required three dimensional calculations to determine the irregular shapes of the 1200 different plates.

The cables joining the deck and pylon are connected by plate brackets at the pylon end on the West face [1].
7 Serviceability

The Sundial Bridge has a full electronic analysis performed [7] continually throughout each day. Tilt monitors are placed in designated areas over the inclined pylon, along with the smaller piers on the South riverbank. These monitors determine any movement on the structure. Also load transducers are placed over the truss system. Alongside these two systems routine visual inspections are performed regularly. This analysis then allows for any replacements or changes to be made to the bridge if any problems arise.

8 Tolerances

With Calatrava designing such a sculpturally complex landmark transferring the idea to a full scale work of art was very laborious. The superstructure of this bridge relies on precise weight and exact position of elements such as the inclined pylon and asymmetric deck. The varying load conditions made the transition from the equilibrium of a sculpture to the equilibrium of the full scale bridge quite challenging. Variations in weight of either pylon or deck would cause major deviations in the equilibrium of the bridge. Any increase in weight of the sundial would result in an increase in moment at its base. Thus low tolerances and precision were required throughout the construction process [6].

8.1 Pre Fabrication

The Trinity and Cascade mountains encircling Redding along with the riparian pine forests and alpine lakes resulted in the onsite fabrication not being possible and as extremely low tolerances were trying to be achieved the bridge lent itself to be prefabricated off site. The steel was fabricated in Vancouver Washington, then shipped by barge to Vallejo and then taken to Redding by lorry. There were 18 section of the triangulated truss deck each of lengths around 12m and 25 loads of pylon, each weighing 30 to 40 tonnes [5].

9 Construction Detailing

With Calatrava only providing design drawings and artistic renders of his proposed bridge scheme construction drawings needed to be produced. The construction design teams, based on these preliminary drawings were then required to complete the construction plans and technical drawings. In total approximately 500 construction drawings were required for the bridge to be realized. These included [8]:

- 3d modeling of the original design concept.
- Mathematical adjustment of the 3d model providing cambering to counteract loads on the structure.
- Detailed descriptions of the individual 1200 steel plates along with their fixings.
- Preparations of the several scale models and the bridge’s construction sequencing.

These unique calculations and technical drawings took 2 years for their completion.

9.1 Construction

The final cost of the Sundial Bridge ended at $23.5 million and this just wasn’t only a financial challenge for the McConnell Foundation but also a construction challenge for all parties involved. The design of the Sundial Bridge required unprecedented precision in construction with very low tolerances in the weights and the positioning of its components. At every stage of construction repeated computer analysis was undertaken taking into account actual weights and the exact geometry of the recently completed elements.

Once foundations were installed the construction of the superstructure began. Firstly the 66m inclined pylon was erected using the prefabricated sections which had been shipped to site. The individual manageable segments could then be lifted into position by crane then welded together in position [9]. In some areas the welding is so complex and the angles so extremely sharp that physically the material could not be welded [10]. This resulted in lots of plates only be welded from one side and needing backing bars. Each bar needed to be calculated to find it specific shape. The pylon is formed from a series of hollow sections allowing each to be filled with concrete to provide the required mass for the bridge system. This concrete is included in the 1900 tonnes [5] of concrete within the foundation. The complexity of this design was induced through Calatrava’s architectural expression.

Figure 12: Construction of inclined member

The method used to erect the bridges 128m main span across the Sacramento River was cantilever construction [9]. With the pylon in position the prefabricated tubular truss deck units could then be incrementally positioned using craning devices. With each units length around 12m its corresponding singular cable could be attached to the transverse bulk heads in the truss and the cantilevered plate bracket on the West face of the pylon. The truss would then be welded insitu to its neighbor and then the cable post tensioned giving the deck stability. From this position then the next unit would be installed until the bridge had span the river.

Temporary propping systems where not allowed in the Sacramento River incase damage occurred to the spawning ground of the Chinook salmon.

This method of construction meant that the pylon and decking were not balanced during erection as the pylon had been firstly fully formed. Moments were therefore created in the base of the pylon during
construction due to its self weight. These moments had to be calculated and the pylon designed to withstand them to prevent the structures collapse during construction.

The construction system would have been far more efficient to synchronize the build of both the decking and pylon incrementally together. This would have then allowed the deck and pylon to be balanced throughout construction but it was not used as this construction method would have taken much longer. To reduce this time the pylon and decking were therefore build individually one after the other.

**Figure 13: Final construction stages**

On completion of the structural skeleton the aqua green opaque glass deck with its granite strips and smooth mosaic white Spanish tiles were installed along with the pedestrian restraint system which mimics the large inclined pylon.

The 14 galvanized steel cables are designed with 100% redundancy so that in the case of failure, maintenance and construction one of the cables can be removed and the others will continue to hold the deck under its own dead weight.

**10 Foundations**

The superstructure of the Sundial Bridge results in the need for a substantial foundation on the North riverside at the base of the inclined pylon while on the South riverside only a small system is required to hold the feet stanchions.

Large bending moments are created in the deck near the pylon and also in the base of the pylon itself due to the lack of backstays. With these bending moments being withstood within the pylon more material is needed to take these large moments and so larger forces need to be transferred to the ground. The bending moments exerted on the pylon are dispersed through the ground by large diameter concrete cast drilled piles [9]. Most live loading along with dead loads exerts longitudinal moments on the pylon while lateral loading induces transverse moments on the pylon and so these 2 different moment directions need to be taken by the pile group along with the axial forces. The inclined pylon supporting the deck transfers 1.36 million kg of pressure to a single 36cm ball bearing set atop the foundation piers anchored 13m deep [11].

The foundation on the South side of the river supports legs which hold aloft the bridge deck after the 128 main span of the river. These legs transfer there torsional moments and axial loads to a smaller pile block which then transfers all moments and forces to the ground below.

**11 Temperature Effects**

Heating and cooling effects on bridges result in large movements of all structural components involved. Stresses are therefore induced in the structure; through movement not being allowed or the temperature variations between top and bottom surfaces.

If the bridge is imagined to be unable to move through expansion due to clogged movement joints and a design value for temperature change in Redding is taken as ±35°C, the free strain of the deck Eq.(20), the stresses in the deck Eq.(21) and deflection Eq.(21) can be calculated.

For footbridges a 50 year return period is adequate and so temperature change can be reduced by 2°C. The coefficient of thermal expansion for concrete and steel is 12×10⁻⁶/°C.

\[
Strain \quad \epsilon = \alpha \Delta T = 12 \times 10^{-6} \times 33 = 396 \mu \varepsilon \quad (20)
\]

\[
Stress \quad \sigma = 210000 \times 396 \times 10^{-6} = 83 N / mm^2 \quad (21)
\]

\[
Deflection \quad \delta = \epsilon L = 396 \times 10^{-6} \times 128000 = 51 mm \quad (22)
\]

These temperature effects also decrease the load carrying capacity of the 14 cables holding the decking in position causing the cables to have a tension loss Eq.(23) and so may create rather large deflections within the deck.

\[
F = \epsilon EA = 420 \times 10^{-6} \times 2.1 \times 10^{-5} \times 2043 = 170 kN \quad (23)
\]

From previous calculation the total tension force in all 14 cables was T=160MN therefore one cable carries 11.4MN and so the tensile force loss is Eq.(24).

\[
\% \text{Tensile Force Loss} : \frac{170}{11400} \times 100 = 1.5\% \quad (24)
\]

This percentile loss can be perceived as negligible because when the cables reach the stage when they lose tensile capacity the tubular truss decking will act as continuous spanning beam. The continuous beam will act between the moment connection at the base of the inclined pylon and at the pier at the other side of the riverbank.

If in the event of all cables failing the deflection in the main span deck would be around 3m and so the bridge would still stand.

As this superstructure is a steel truss with a glass decking the temperature profile of the system will follow a Group 2 shape (BS 5400-2:2006).

**12 Wind Loading**

The hourly wind speed in the Redding area 10m above the ground is 34m/s. This is predominately due to the surrounding topography with the Trinity and Cascade mountains nearby.

All wind loading is analyzed using BS 5400.

The dominant wind direction in the area of the Sundial Bridge is from the East direction and so the
dominant wind direction factor is 0.74. As the footbridge is for a 50 year period $S_d=1$.

Site hourly mean wind speed $V_s$ Eq.(25), gust factor $S_g$ Eq.(26), max wind gust speed $V_d$ Eq.(27):

$$V_s = V_b 	imes S_p 	imes S_a 	imes S_d = 34 \times 1 \times 1 \times 0.74 = 25 \text{ m/s}$$

$$V_d = S_g \times V_s = 1 \times 25 = 25 \text{ m/s}$$

$$S_g = S_p \times S_a \times S_h = 1.2 \times 0.81 \times 1 = 1$$

As the Sundial Bridge has an open parapet $d=2.2\text{ m}$ (depth of truss) and using this it is possible to calculate the transverse wind load. The dynamic pressure head $p$ Eq.(28), total side area of deck $A$ Eq.(29), solidity ratio $\eta$ Eq.(30) spacing ratio $g$ Eq.(31), shielding pressure head $S$ Eq.(27), total side area of deck $A$ Eq.(29), solidity ratio $\eta$ Eq.(30) spacing ratio $g$ Eq.(31), shielding factor $S$ Eq.(32) and drag coefficient for a single truss Eq.(33) provide the data necessary to calculate the nominal transverse wind load Eq.(34):

$$q = 0.613 \times V_s^2 = 0.613 \times 25^2 = 383 \text{ N/m}^2$$

$$A_i = dL = 2.2 \times 213 = 469 \text{ m}^2$$

$$108 = \frac{7}{0.3} = 3.2$$

$$g = \frac{2}{2} = 1$$

$$\eta = 0.8$$

$$P_i = q \times A_i \times \eta \times C_d = 383 \times 469 \times 0.8 \times 3.2 = 460 \text{ kN}$$

$$P_i = 2.2 \text{ kN/m}$$

This wind loading for a bridge is relatively low purely because of the open structure truss system and the open parapet design.

### 12.1 Longitudinal Wind Loading

Using BS5400 the longitudinal wind load $P_l$ calculates the nominal longitudinal wind load on the superstructure of the bridge Eq.(35). As there is no vehicle traffic on the bridge the $P_l$ can be ignored. The depth $d$ is taken as 2.2m.

$$P_{lb} = 0.5 \times q \times A_i \times \eta \times C_d = 0.5 \times 383 \times (2.2 \times 7) \times 0.8 \times 3.2$$

$$P_{ls} = 7.5 \text{ kN} = 1.1 \text{ kN/m}$$

### 12.2 Nominal Vertical Wind Load

The force of the wind lifting the bridge or pushing the bridge downwards is calculated below Eq.(36).

$$P_v = q \times A_i \times C_1 = 383 \times (7 \times 213) \times 0.4$$

$$P_v = 228 \text{ kN} \approx 1.1 \text{ kN/m}$$

### 12.3 Seismic Loads

It can be believed that the maximum wind load on the system is larger than the seismic loading and so it can be assumed that static wind loading will be the critical loading case on the superstructure and so seismic loads can be ignored as it is safe to assume that neither will act together.

### 13 Natural Frequency

Vibrations in pedestrian bridges are an important issue and to discover the vibration frequency of a pedestrian bridge under service limit state conditions the equations in BS5400 are used.

Fundamental natural frequency using the Raleigh Ritz method Eq.(37), evaluating using superimposed dead load but excluding pedestrian live load. The main span is 128m.

$$f_0 = \left( \frac{c^2}{2 \times 3.14^2} \right) \times \left( \frac{E \times I \times g}{M} \right)^{\frac{1}{2}} = 36 \text{ Hz}$$

As the fundamental natural frequency exceeds 5Hz for the unloaded bridge in the vertical direction the vibration serviceability is deemed to be satisfied. With the natural frequency being less than 75Hz psychological effects will not affect users of this footbridge.

In the horizontal direction 1.5HZ for the loaded bridge is exceeded and so little excitation shall occur laterally.

### 14 Susceptibility to Intentional Damage

There are 6 security cameras [12] strategically placed over the Sundial Bridge and constant foot patrols by Turtle Bay Staff result as the first line of defence against acts of vandalism toward the bridge. The bridge itself is designed to be resistant to vandalism by ensuring fixings and fasteners are out of site and cannot be loosened simply and quickly using minimal tools. This then stops pieces of the bridge from being removed and also with the fixings being hidden stops connections being damaged by blows with implements.

The pedestrian restraint system is resistant to vandalism due to it being designed to withstand loads 50% greater than the design load calculated for it. This then prevents vandals from being able to swing on the guardrail and cause it to break.

Graffiti on every bridge is most annoying to designers and users but this low level act of vandalism is reduced within the sundial bridge as only the inclined pylon produces a large plan area to use as a canvas. The tubular truss system produces little surface area and the base of the pylon being in full view within the sundials plaza is a huge deterrent leaving little privacy for vandals to partake in such an antisocial act.

### 15 Durability

With the Sundial Bridge expected to carry over 100,000 pairs of feet each year, the durability of the footway needed to be heavily considered. The glass panel decking needed to be hardy enough to deal with spillage, impacts and gradual wear and this guided the designer’s attention toward structural glass.

Many factors affecting durability are controlled purely by the cleaning and continual maintenance of the structure. As a result the city spends $145,000 a year to
clean [12] and patrol the bridge purely to enhance the longevity of the structure.

As the integrity of the bridge has a large reliance on the steel galvanised cables it is of upmost importance the cables are regularly monitored. With the cables being galvanised they are protected against corrosion by a physical barrier although in years to come it is possible for the upper layers of the cable to degrade and therefore even though these galvanised cables are considered low maintenance regular inspection is crucial.

As the tubular truss system and inclined pylon are constructed from large volumes of steel, corrosion protection from acid rain and possibly the de-icing of the bridge deck was crucial. With there being near 1000 tonnes of steel [5] it was too costly to galvanise every piece and so a thorough paint system was required. All the steel is given a three coat paint system with a white epoxy final coat [4] except the stainless steel rods and pipe used for the bridge railing.

16 Future Changes

The final finishes applied to the structure such as lighting has been controversial amongst many people and possibly a future change may be removing some of the down lighting fixtures. The environmentally sensitivity with respect to down lighting has resulted in recent research into the effect of this light pollution on the salmon spawning grounds and its adverse effect on salmon eggs. To avoid any future uproar it is possible that these lights will be silently removed in the near future.

With regards to the decking, the aqua green translucent glass fulfils its aesthetical job while also preventing shadows being cast on the river below. One problem that has come to fruition is their durability because longer life expectations were anticipated. Many panels have cracked under unknown circumstances leaving sharp glass splinters protruding that give potential problems to users [12]. To stop these problems arising in the near future it is possible that the whole decking will be changed to some other material enhancing the overall endurance of the deck.

17 Conclusion

This Sundial Bridge would have been more successful if it had satisfied the ideals of structural art. Structural art has 3 dimensions scientific, social and symbolic. Scientific = Efficiency, Social = Economy, Symbolic = Elegance [1]. To be a work of structural art all must be satisfied.

Efficiency: The Sundial Bridge lacks efficiency by requiring vast amounts of needless material which could have been avoided with just a single back stay.

Economy: The final price of the bridge resided at $23.5 million which is around 800% over its initial budget with an outstanding cost/m² of $15220/m².

Elegance: The footbridge is aesthetically pleasing appearing lightweight, slender and sensitive to the environment. It is even considered unique by having an offset pylon on one side of the deck.

Although the Sundial Bridge only conforms with the symbolic portion of structural art the bridge itself has fulfilled its role in enticing tourists to Redding and increasing its economy. The outcome has been an extraordinarily expensive footbridge that could with a change in design, have resulted in a more economical bridge that would have satisfied Redding's needs.

Rarely do architects have an opportunity to create landmarks significant enough to redefine a cities image from a blank canvas with so few restraints. As a result Calatrava produced a faultless design which has exceeded in its purpose of placing Redding on the map. Cost and efficiency are major boundaries for designers these days and it is great to see what can be done when they are given a free rein and I believe Calatrava has produced for Redding a world gem that must and will be cherished forever.

References