Abstract:

This paper aims to evaluate the design and construction of Tsing Ma Bridge in Hong Kong. Tsing Ma Bridge is the longest suspension cable bridge which carries both rail and road traffic. There are eight highways in total, six on the upper deck and two on the lower deck, with two railway tracks on the lower deck. The bridge has become one of the landmarks in Hong Kong due to its structural achievements and the night view of the bridge. Aesthetics of the bridge were thought about during design. The major problem of Tsing Ma Bridge was to withstand the excessive wind, typhoon. To overcome the excessive wind, bridge design had changed from one single deck into two level decks. The whole construction of the longest rail and road suspension cable bridge was completed within five years. There were five major construction components which are anchorages, approach span, foundations and construction of bridge tower, main cables and suspended deck. There is a Wind and Structural Health Monitoring System (WASHMA). This system is used to monitor the bridge closely to make sure the bridge is safe. With this system, quick decisions can be made.

Keywords: Aerial Spinning Process; Construction; Design; Long span bridge; Typhoon; Wind and Structural Health Monitoring System (WASHMA)

1 General Introduction

Tsing Ma Bridge is a bridge connecting Tsing Yi Island and Man Wan Man-Made Island, which also where the name comes from. It was one of the infrastructural works of the Hong Kong Airport Core Programme. This Tsing Ma Bridge is an important link between Hong Kong mainland and the Hong Kong International Airport. Initially, it was planned to have an under-water tunnel to carry the airport traffic. However, the channel was thought to be too deep and the heavy shipping traffic at the surface would make the under-water construction too dangerous to under-go. Therefore, a suspension bridge was built instead which is the Tsing Ma Bridge.

Tsing Ma Bridge is the world’s sixth largest suspension bridge but the world longest span suspension bridge which carrying both road and rail traffic. The bridge is supported by gravity-anchor in the form of reinforced concrete. It is situated in Hong Kong and it is 2.2km long. It was first constructed in May 1992 and finished in May 1997. It costs US$ 1 billion.

Tsing Ma Bridge is a double-decked suspension bridge and carries a total of 8 lanes of road traffic and 2 MTR rail lines. Its main span has a length of 1,377 metres which makes Tsing Ma Bridge the largest of all bridges in the world carrying rail traffic. It has the width of 41m with a height of 206m. The clearance height of the bridge is 62m so the bridge does not interrupt barges going through the Ma Wan Channel.

2 Aesthetics of the Bridge

2.1 Function

Tsing Ma Bridge has fulfilled its function. It is the important connection between Hong Kong and Hong
Kong international airport on Lantau Island. On the upper deck, there are 6-lanes of automobile traffic with three lanes in each direction. On the lower level, there are two rail tracks and two sheltered carriageways. During inclement weather such as typhoons, the upper deck will be closed. If the wind speed is still within acceptable level, the two sheltered carriageways on the lower deck will be open to maintenance access and used as emergency roadway, so traffic will not be interrupted from or to Hong Kong International Airport.

The bridge is designed to have a design life of 120 years. 49,000 tonnes of structural steel and 450,000 tonnes was used for the construction of the bridge which has a total cost of US $1 billion to build. Also, the material was fabricated and assembled oversea, therefore it was essential to minimize the total amount of material while maximised all the structural benefits.

2.2 Proportions

The total length of the bridge is 2160m with its longest span of 1,377m. The width of the Bridge is 41m with the tower of 206m high. The depth of the deck section of 7.6m is 62m above the water level. For the balance of geometric between depth and span and between height, length and spans are balance so that the bridge does not look odd. The bridge does seem to be supported on two towers since the dimensions look correct as does the overall depth. Also, the bridge has a good impression that the masses and the voids is balance.

![Figure 1: Elevation of the Tsing Ma Bridge](image1.png)

2.3 Order

There is a stainless steel cladding along the external faired edges of the deck, so the final external appearance of the Tsing Ma Bridge is a box with faired edges with continuous gaps along the top and bottom surfaces whereas inside, it has the appearance of conventional truss work. The hanger cables are not too close together each other, so the bridge does not look as if it has too many lines.

2.4 Refinements

The four approach spans on the Tsing Yi side are each 74m long and the approach spans on the Ma Wan side are 63m and 76.5m whereas the main span is 1,377m. This means the bridge has smaller span near the abutments and so it keeps the aspect rations of the “rectangles” between the deck, ground and pier constant and as a result appealing. The oblique angles of view also do not create an opaque barrier, since there are no more than 2 columns across the width of a bridge deck.

2.5 Integration with environment

Tsing Ma Bridge does not integrate with the surrounding environment, the designer of the bridge, Mott MacDonald, did not want the bridge to integrate with the environment. This significant engineering work has not become a popular tourist sight but also a famous landmark. There is a viewing platform near the bridge, so visitors can view Tsing Ma Bridge at a distance even at the day time.

2.6 Texture

The suspension cables were wrapped around with galvanized wire and then epoxy paste was added to provide the waterproof protection to the cable. The deck of the bridge was cladded with stainless steel cladding panels to provide the best stability during high wind time. The two bridge towers and piers were constructed using reinforced concrete. Therefore, overall, all the components’ texture is smooth finished.

2.7 Colour

The colour of the bridge is nature since it was not painted. Therefore, it was not needed to on-going to paint or touch up paint the bridge. However, there is a system of decorative lighting installed on top of the suspension cables of the bridge. This lighting contains more than 1000 special lighting units and each unit can mix the three primary light, red, blue and green, to induce any desired colour. Therefore, at night, using different lighting effects, the shape of the bridge can be transformed. This selective application of orchestrated architectural lighting scheme operates from 6.00pm to 12.00 midnight in autumn and winter season while in spring and summer season, it operates from 7.30pm to 12.00mid-night. When the bridge is lit and as it is close to the water the light reflects making the bridge look more spectacular and makes Tsing Ma Bridge a favourite scenic spot.

![Figure 2: Night view of the spectacular decorative light on Tsing Ma Bridge](image2.png)
2.8 Character

Being the world’s sixth longest suspension bridge and the longest span rail-road suspension bridge, Tsing Ma Bridge surely has its character, with its architectural lighting, making the bridge looking magnificent. Tsing Ma Bridge has become one of the landmarks of Hong Kong as well as a popular scenic spot.

2.9 Complexity

The design of Tsing Ma Bridge looks very simple. It looks like a normal suspension bridge. The design of the bridge was led by Mott MacDonald which also is the consulting engineers of Tsing Ma Bridge. Therefore the design of the Tsing Ma Bridge is more functional instead of too fancy. Also, there were 20 innovations for Tsing Ma Bridge whereas 9 design innovations and construction innovations, such one anchorage innovation.

3 Construction

The whole construction of the two decks Tsing Ma Bridge was commenced on 25 May 1992 and was completed in May 1997. The construction of the longest span bridge in the world which carries both rail and road traffic was completed within 5 years time was amazing. The contractor is Dorman Long Technology Limited with 3 co-contractors and 5 subcontractors and Sir William Halcrow & Partners Ltd has the responsibility of construction management. The whole contract sum was US$1 billion which is a fixed price lump sum contract. It was initially a single deck bridge but after the wind tunnel test, the design has changed into a two decks bridge with no extra time to build, so it had a difficult technical constraints and a very tight schedule.

The two portal braced rein-forced-concrete bridge towers were first erected (see 6.1) and were went up like skyscrapers having a height of 206m which is equivalent of about 60 storeys. It was first planned to hang the heavy suspension cable from the two towers to support the massive decks but due to the main cable is 1.1m diameter and each weight 13,000 tonnes so it was impossible to have the cable assembled on the ground and put into place. Therefore, the big cables were built in air using aerial spinning process (see 6.4). During this early stage of the project, the bridge will become very unstable and dangerous during extreme weather such as the typhoon, and can damage and break the wires and lead they to go everywhere in the air. Therefore, the 86,00km of steel cable in the air was constructed under 9months without any interruptions by extreme weather. After the cables were secured in place, the bridge deck was installed (see 6.5). The deck construction was started at the centre and working out toward the tower.

3.1 Major Components

There are five major components in the Tsing Ma Bridge construction and they are; anchorages on both ends of the bridge, approach span on Tsing Yi side, foundations and the construction of the two bridge towers, main cables and suspended deck.

3.1.1 Anchorages

There are two large gravity-type anchorages which situated at both ends of the bridge and are used to take the pulling forces from the main suspension cables and the load of the main suspension cables. The two anchorages are also used to receive and support the bridge approaches as a bridge abutment. Furthermore, after the gravity anchorage on the Tsing Yi side was back-filled with soil, it is used to serve as a coupling structure in the expansion joints of slip roads and rail track which allow the in and out flow traffic to the airport and Hong Kong centre.

Before the anchorages were constructed, pit has to be excavated on the ground and seabed. These very large concrete structures are seated on the bedrock deeply, 20m below sea level and 55m deep, on the landside of Man Wan Island and Tsing Yi Island. The total weight of the concrete that used in the Ma Wan Anchorage tonnes and the Tsing Yi Anchorage is 250,000 and 200,000 tonnes. There is strand shoe at the bottom of the cable chamber on the anchor structure where the connection of the main suspension cable and the gravity anchor are. The main structure of the two anchorages was completed when the suspension cables were connected.
3.1.2 Approach span on Tsing Yi side

There are two bridge approach spans on Ma Wan side which are 63m and 76.5m. On Tsing Yi side, there are four 72m spans which supported by two sets of reinforced concrete piers on the land side which was connected to the deck of the bridge from bridge tower to the bridge abutment. Making the overall Tsing Ma Bridge has a length of 2160m.

The first span was put together on the ground and then using strand jacks arrangement, it was raised and put it into position. Further construction was done and the final section of the span was then stationed in smaller sections on the deck level using derrick cranes due to the limitation of flat working space on the ground level. Due to the thermal movement, there is an expansion joint located inside the approach span section so that the maximum thermal movement of +/-835mm is allowed. This is like the suspended deck in form and cross-section (will be mentioned on next page, See 3.1.5), however, this approach span was not supported on cable-support but the piers head. The final stage of the approach span was to clad stainless steel cladding panel.

3.1.3 Foundations and the construction of the bridge tower

There are two identical towers, one is located on the man-made island which is about 130m away from the coast of Ma Wan Island and the other tower is located on the Tsing Yi Island. The Tsing Yi tower foundation is just simply spread footing on the rock whereas the tower on Ma Wan side is founded on two precise concrete caissons resting on prepared rock seabed in about 12m depth of water. Both towers are 206m height and constructed with reinforced concrete of 50MPa strength which is concrete grade 50/20. Each tower leg is 6m wide and tapers from 18m to 9m in longitudinal direction. The legs are reinforced concrete. Using self-lifting formwork system, the construction was continually 24 hours a day until the leg structure was finished. The slip form system is used in a continuous process which lasted 3months. There was temporary jetty allowing the delivery of the bridge components and materials. The two towers are both two-legged and after the completions of the leg structure, four steel trusses at the intervals in the form of the portal beam design were installed, so that it will improve lateral resistance from wind loads. On top of each tower, a set of cast steel saddle was installed to support the suspension cable. Using strand jacks, the 500-tonnes cast steel saddle was lifted to the top. Finally, reclaimed material was used to over the caissons.

3.1.4 Main cables

The main suspension cables were constructed by a process called “Aerial Spinning Process”. The main cable is 1.1m diameter which was formed by a total of 70,000 galvanised high tensile steel wires of 5.38mm diameter. 160,000km of wire was used on the whole bridge which can circle the earth four times. A temporary footbridge from anchorage to anchorage was constructed before the process started. The initial strands had to be lifted to the two towers tops and placed by “high-lining”. This process consisted of drawing the galvanised wires from a constant-tension supply, then pulling loops of these wires from one of the anchorage to the other anchorage. Finally, passing 500 tonnes cast steel saddle on top of the bridge towers seating the cable. Each suspension cable was split into 97 strands which one strand consisted 368 of galvanised so the difficulty of the process reduced. Straight after, Individual cable was compacted into circular section and bounded with temporary strapping, so they were not overlapped or twisted. After this, cast steel cable bands were clamped into position at 18m interval by tightening bolts which also support the suspender cables hanged the deck below. The main suspension cable was connected onto the strand shoe at the end and housed inside the stainless stain hood at the top of the bridge tower. This accommodates the cable geometry and transfers their loads to the towers. Lastly, the main cable was wrapped around by the galvanised wire using a wrapping machine then epoxy paste was added to provide waterproofing protection to the cable. The temporary
footbridge was then removed after the final check on the main cable.

Figure 6: Cast-iron cable band was fitted so it clamped the strands of the main cable in position.

3.1.5 Suspended deck

The length of the main span is 1377m from tower to tower and there is only one suspended side span on Ma Wan side which is 355m. The suspended deck is suspended from the main cables at 18m centre-to-centre. There are two lengths of 76mm diameter wires which are wrapped over the grooved cable bands clamped onto the main suspension cable. The upper level carriageway has the surface of 40mm thick mastic asphalt over waterproofing whereas the lower level carriageway has an additional 7mm thick epoxy layer.

The deck structure was fabricated in Britain and Japan and then was brought to further processed and assembled in China into standard steelwork deck modules. The 96 modules in total were prepared, each weight 480 tonnes and 18m long. Each was a box-shaped modular section. After, the completion of the spinning the main suspension cable, each deck modules were shipped from the site on river side of Dongguan by specially designed barges. The special barge was towed and with the position fine-tuned below the bridge and the help of tug-boats, deck modules were raised onto the exact position from the barge to the deck level. A pair of strand jack gantries was used to manoeuvre along the main cable, so the deck modules were able to raised from 60m below and then was connected to the partly aligned bridge. The aerodynamically designed stainless steel cladding panels were assembled on the side of the bridge deck so the deck received the best stability under high winds. Lastly, the hanger cables were connected to the deck.

Figure 7: At Dongquan, a completed deck module at assembly yard before delivery to Hong Kong

Figure 8: Installation of the first deck module which as transported in pair to the site by barge. Strand jack system was used to mount on the main cable to raise the deck.

Figure 9: Structural steel deck of approach span section

3.1.6 Railway track work

The 2,142m of double-track on the lower level deck was installed by Gammon Construction Ltd. The installation of the railway tracks was started when the connection of the erected deck modulus had commenced. There are 476 track-form bearer units; each has the length of 9m and the weight of 9 tonnes. Each track-form bearer units are supported by eighteen special adjustable bearing assemblies with eight lateral bearings and four longitudinal bearings which holding each unit in position. Special welding equipment was used to weld the railway track together. The special welding equipment was mounted on a train car so it can move along the track and speed up the process. Temporarily aligned rail was secured by the pre-cast blocks and then was embedded in reinforced concrete curb.

4 Maintenance
There are routine maintenance inspections and they are done by the Highways Department’s inspectors. They have to work on the inclined cables to examine and record every defect so maintenance can be arranged. Due to the working at heights, safety requirements are crucial, for example safety belts. Unlike other common vehicular bridges, Tsing Ma Bridge has tall towers, stay cables and the deck which is more than 60m above the sea. Due to these features of the bridge, traditional methods and equipments, such as using hoists or erecting scaffolds, cannot be used to reach every corner of the bridge.

Therefore, special access equipments are used to inspect and maintenance every corner of the bridge. For the bridge towers’ external surface, working cradles are used which is suspended from the tower top (see below Figure 10).

![Figure 10: Moveable tower inspection cradle](image)

There are moveable gantries underneath the bridge which act as a working platform for inspections below the road decking which can travel along the whole length of the deck (see Figure 11).

![Figure 11: Moveable platform below the road decking](image)

Moveable cable cradles are used to maintenance the stay cables. When it needs to be used, it assembled from small pats on the bridge deck and lifted onto the main suspension cables. After the cradle has been set up, a short distance will be walked along the main suspension cable before getting on the cradle. Then the cradle can be used to travel any point on the cables (see below Figure x).

![Figure 12: Moveable inspection cradle](image)

On the lower deck, the two emergency roadways are also used as the maintenance access as well as the backup for traffic during extreme weather. When maintenance works need to be done on the upper deck road’s surface, one lane will be close at each time and the motorists will be advised to use the lower deck.

5 Loading

Special load conditions need to apply on Tsing Ma Bridge since it is in a region with high seismic activity such as seismic load, $K_h$, 0.05g. Also, due to the man-made island, there is a ship collision load of vessels 220k DWT. However, winter condition, such as snow load, does not need to be considered. The design wind load is 50m/s and 80m/s for the design gust wind speed. The live load is six highways on the upper level and two highways and two high speed rails on the lower level. The maximum speed for automobiles is 100km/h and for the rail, it is 135km/h and was designed to use 20kN/m per lane and has a wind gust speed of 85m/s.

5.1 Calculations of loading

However, the calculations below show simply calculations done by hands.

The distance between hanger cable and hanger cable is 18m, so the span is assume to be 18m.

**Table 1: Live traffic loads**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ha loading</td>
<td>30.0kN/m</td>
</tr>
<tr>
<td>Hb loading</td>
<td>250kN/m</td>
</tr>
<tr>
<td>Knife-edge load, KEL</td>
<td>120kN</td>
</tr>
</tbody>
</table>

**Table 2: Factorised live traffic load**

<table>
<thead>
<tr>
<th>Factor Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial factors, ( \gamma_1 )</td>
<td>1.25</td>
</tr>
<tr>
<td>Partial factors, ( \gamma_2 )</td>
<td>1.10</td>
</tr>
<tr>
<td>Factorised Ha loading (total)</td>
<td>96.25kN/m</td>
</tr>
<tr>
<td>Factorised Hb loading</td>
<td>302.5kN/m</td>
</tr>
<tr>
<td>Factorised KEL</td>
<td>145.2kN</td>
</tr>
</tbody>
</table>

\[
v_c = v K_1 S_1 S_2 \]

**Table 3: Maximum wind gust**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean hourly wind speed( v )</td>
<td>35m/s</td>
</tr>
</tbody>
</table>
Wind coefficient, $K_1$ | 1.50
Funnelling factor, $S_1$ | 1.36
Gust Factor, $S_2$ | 1.0
Maximum wind gust, $v_c$ | 71.4 m/s

$$P_t = q A_1 C_D$$  \hspace{1cm} (2)

**Table 4: Horizontal wind load**

| Dynamic pressure head, $q$ | $0.613 v_c^2$ |
| Solid horizontal projected area, $A_1$ | 9914 m$^2$ |
| $b/d$ | 41/7.2 = 5.70 |
| Drag coefficient, $C_D$ | 1.29 |
| Horizontal wind load, $P_t$ | 39,965,813/1377 = 29.0 kN |

$$P_v = q A_3 C_L$$  \hspace{1cm} (3)

**Table 5: Vertical wind load**

| Plan area, $A_3$ | 41 x 1377 = 56,457 m$^2$ |
| Lift coefficient, $C_L$ | 0.4 |
| Vertical wind load, $P_v$ | 70,571,250/1377 = 51.2 kN/m |

**Table 6: Factorised wind load**

| Partial factors, $\gamma_1$ | 1.10 |
| Partial factors, $\gamma_2$ | 1.10 |
| Factorised horizontal wind load | 35.09 kN/m |
| Factorised vertical wind load | 61.71 kN/m |

$$\text{Design dead load} = \gamma_1 \times \gamma_2 \times \text{dead load}$$ \hspace{1cm} (4)

**Table 7: Dead load**

| Partial factors, $\gamma_1$ | 1.05 |
| Partial factors, $\gamma_2$ | 1.10 |
| Dead load (assumed) | 150 kN/m |
| Factorised dead load | 173 kN/m |

$$\text{Design super} = \gamma_1 \times \gamma_2 \times \text{super imposed dead load}$$ \hspace{1cm} (5)

**Table 8: Super imposed dead load**

| Partial factors, $\gamma_1$ | 1.75 |
| Partial factors, $\gamma_2$ | 1.10 |
| Super imposed dead load (assumed) | 20 kN/m |
| Factorise super imposed dead load | 39 kN/m |

**Table 9: Total factorised load**

| Factorised HA loading (total) | 96 kN/m |
| Factorised HA loading | 303 kN/m |
| Factorised KEL | 145 kN |
| Factorised vertical wind load | 62 kN/m |
| Factorised dead load | 173 kN/m |
| Factorised super imposed dead load | 39 kN/m |

Load at middle of hanger cables:

\[ (96 + 173 + 39)18 + (303)4 + 145 = 6900/2 = 3450 \text{kN} \]

Moment at middle of hanger cables:

\[ 3450 \times 9 - [(308)9 \times 9]/2 - 303(7.3 + 5.5) = 14,700 \text{kNm} \]

$$M = \sigma \cdot I / y$$  \hspace{1cm} (6)

**Table 10: Design Moment**

| I (assumed) | 365 m$^4$ |
| Stress of high tensile steel, $\sigma$ | 460 kN/m$^2$ |
| $y$ (assumed) | 4.6 m |
| Design moment | 36,500 kNm |

As the table 10 shown, the bridge was designed to take 36,500 kNm of moment whereas the bridge is taking 14,700 kNm. Therefore, the bridge ideal will not fail due to sagging or hogging.

**6 Strength**

Each cable carries a load of 53,000 tonnes.

The deck section is steelwork and is structurally a hybrid arrangement having both truss and box forms. There are two longitudinal trusses to the entire depth of the deck at 26 m centres acting in conjunction with the upper and lower level decks to provide vertical bending stiffness. There are also plan diagonal bracings at the upper and lower carriageways allowing the trusses to provide lateral bending stiffness.

**7 Serviceability**

The power and communication cables were installed inside the bridge deck. There are two service lanes on the sides of the deck where all the basic services ducts and cables for the bridge are.

**8 Temperature**

The average minimum temperature in Hong Kong is 13°C in January and February whereas the average maximum temperature is 31°C in July and August. The minimum record temperature is 0°C in January and maximum record temperature is 36°C in August.

$$\delta = \alpha \cdot \Delta T \cdot l$$  \hspace{1cm} (7)

**Table 11: Deflection in deck due to temperature**

| Coefficient of thermal expansion, $\alpha$ | $12 \times 10^{-6} / ^\circ \text{C}$ |
| Maximum temperature | 36°C |
| Minimum temperature | 0°C |
| Change in temperature, $\Delta T$ | 36°C |
| Length of the span, $l$ | 1377 m |
| Deflection in deck, $\delta$ | 50 mm |

**Table 12: Deflection in tower due to temperature**

| Coefficient of thermal expansion, $\alpha$ | $12 \times 10^{-6} / ^\circ \text{C}$ |
| Maximum temperature | 36°C |
| Minimum temperature | 0°C |
| Change in temperature, $\Delta T$ | 36°C |
As the table 11 and table 12 shown, the deflections in the deck and the two bridge towers are not very large.

9 Creep

Creep in bridge members is not a sudden process. There are always deflections in a bridge. The bridge has deformations and displacement under a variety of loading conditions. Although, the bridge was designed to have enough resistance against typhoon, the excessive wind load would still have fatigue damage to the bridge especially the rail and road traffic were still continued. However, all these deformations and displacements does not create hazardous conditions for the traffic on the bridge. Also, there is a Wind and Structural Health Monitoring System (WASHMA), which will be discussed in detail later on (See 11 Durability), to monitor the bridge closely so the bridge will always be in a safe condition. Yet, as these deformations and displacements increase in size, they will have an effect on the bridge’s structural integrity and the maintenance needs.

The creeping process is under a high-cycle and the deformation in the structure is elastic since the stress does not have a great effect on it. The rate of fatigue damage can be written as:

\[
\dot{D} = \begin{cases} 
\frac{\sigma^2 - \dot{\varepsilon}^2}{2} \frac{1}{\sigma (1-D)^{\alpha}} & \text{for } \sigma \geq \sigma_f \\
0 & \text{for } \sigma < \sigma_f 
\end{cases}
\]  

where as D is variable for fatigue damage, B, α and β are the material constants and σ is the damage equivalent stress.

10 Wind

Tsing Ma Bridge is the first long span suspension bridge build in typhoons region, therefore one of the major problems of Tsing Ma Bridge is it needs to withstand one of the most destructive forces on earth, typhoon wind, which has the speed of 300km/h. There are as many as 8 typhoons each summer in Hong Kong, therefore it was essential to first prove the bridge’s strength in laboratory. To understand how the wind would affect the structure, engineers created a computer model. This computer model stimulated the motions of the suspension bridge in 65km per hour wind and was amplified 1000 times. This allows the engineers to understand and identify how the deck would react and move.

After collected all the data from the experiments, engineers were then built a detail scale model and placed it in an extensive wind tunnel so that experiments are carried out to develop the best arrangement to ensure the bridge’s aerodynamic stability in typhoon winds. A 1:80 scale section model of the deck was used for the erection stage and a 1:400 scale full aeroelastic model of the entire bridge. The aim of the wind tunnel studies was to show the safety of the bridge under construction and once completed, both with respect to aerodynamic stability and the possible effects of the excessive typhoon wind speeds. Also, dynamic response data was provided at a few key locations so that it can compare with the full scale data from the non-stop monitoring program managed by the Highways Department of Hong Kong. When the full model was experimented in varied stages of construction in turbulent boundary layer model flow, it was then complete with the local topography to model the wind conditions at the site.

The model tests identified critical stages of erection which let the construction program of the bridge to be tailored to keep away from the typhoon time. Having compared the model experimented results and the full scale monitoring, the engineers are allowed to understand better the behaviour of the bridge in the wind. After the experiments, engineers realised the initial one deck bridge design was dangerously unstable under the high wind speed. Since the bridge cannot be made shorter so it was thought to make it heavier. Therefore, under the main road deck, a lower level was added for the rail and the two lanes traffic. Also, a compact streamlined and vented deck cross-section was developed to improve the aerodynamic stability of the bridge, especially in typhoon times. This design stiffens the bridge and solves the potential problems and added the traffic capacity.

The deck structure is aerodynamically stable in winds up to typhoon speed which is has a one-minute mean wind speed of around 95m/s. There are some ties on streamlined box deck section. These ties are central ventilation openings; they have not only provided skylight for the airport railway but also acts as a pressure balance to reduce the wind effect during high wind time. Cross frames of Vierendeel form are at 4.5m centre-to-centre foe every fourth frame being supported by the suspenders. To control the air flow across the deck, there is stainless steel cladding along the outer edges of the deck.

Wind deflectors were added to protect the lower deck from the winds which blow off the South China Sea. These are 531,600 wind deflectors which are some 1,000 tonnes of 1.5mm thick trapezoidal-shaped corrugated. They channel winds above and below the lower level deck; regular gaps are present between the deflectors so that the pressure is equalized inside and outside the deck. The wind deflectors have a low-reflectivity 2D finish. There are triangular nosed wind splitters so wind loads can be minimized. They are also used for the panel and the splitters structural attachments. The wind splitters and the structural members have a hot-rolled annealed and pickled finish.

There are a total of 4 numbers of steel trusses in between the legs of the towers so lateral resistance against the wind loads increases.
11 Durability

On Tsing Ma Bridge, the Wind and Structural Health Monitoring System (WASHMA) is used to monitor the bridge closely to make sure the drivers are feeling comfortable and safe. This system allows the Highway Department to have an early warning, so the bridge can be increases its durability, integrity and reliability.

This WASHMS is made up of 4 different systems and they are: Data Acquisition System, Global Central Computer System, Local Centralised Computer System and Sensory System. On Tsing Ma Bridge, there are more than 350 sensors and their relevant interfacing units so the structural behaviour of the bridge is observed 24 hours everyday of every week.

The 350 or more sensors include accelerometers, anemometers, displacement transducers, dynamic weight-in-motion sensors, level sensing stations, strain gauges and temperature sensors. All these 350 and more sensors are used to measure everything from tarmac temperature and strain in structural members to the wind speed and the deflection and rotation of the kilometers of cables and any other movement of the bridge decks and towers. These sensors are used as an early warning system for the bridge, allowing necessary information which helps the Highway Department to monitor closely and more accurate the general health conditions of the bridge.

The information from these different sensors is then transmitted to the three data acquisition outstation units on the bridge. The administrative building which used by the Highway Department in Tsing Yi is where the computer power house for the system located. Data collection control, post-processing, storage and transmission are being provided by the local central computer system. The global system provides data acquisition and analysis, assessing the physical conditions and structural functions of the bridge and for integration and manipulation of the data acquisition, analysis and assessing processes.

Having this WASHMA, quick decisions can be made on action to deal with imperfection analysis of measured data and any actions that regard operations and maintenance of the bridge. It was considered the existing system should have upgraded to provide more efficient data but due to the complexity of the new system will need a different level of computing power so it was not being updated.

12 Susceptibility to intentional damage

There are a total of 62 bearing in Tsing Ma Bridge. They were added and used to support the bridge’s deck, so movements due to temperature variations and other external forces, for example wind load, are allow. In 2000, however, during one of the routine maintenance
inspection, a thin layer of plastic material was squeezed out from one of the bearing pad. Therefore a replacement was added. The elliptical extrusion grew to about 250mm in length within a month’s time. With all the advices of independent experts, the failed bearing was replaced after 7 months and has been functioning pleasingly since then. During the replacement process, the bridge has been safe and had no disruption to both vehicular and rail traffic.

There had been a few reports that people have been jumping off the bridge to commit suicide, so proposals such as installing safety nets under the bridge, were suggested so it will reduce or even stop people jumping off the bridge to commit suicide. Yet, Tsing Ma Bridge has no sidewalk, so it is not readily accessible by the public. If the safety nets were added to the bridge, the stability of the bridge would be affected particularly under excessive wind conditions and they would also obstruct the routine inspection and inspection and maintenance of the bridge deck. Therefore, the solutions for it are to increase the frequency of patrolling on the bridge and when the operation of the bridge is being monitored through the close circuit television, staff should be more alert.

13 Possible future changes which the bridge have to undergo

The width of the deck could not be expanded due to the shape of the aero-dynamical shaped deck section and the bridge towers. If the capacity of the bridge increases and reach the full capacity, the two lanes on the lower level deck can be opened and used. However, if both level decks are in full capacity, an extra bridge could be built next to the existing Tsing Ma Bridge.

When the bridge was designed, the effects of earthquake were not considered since Hong Kong is not in the zone of earthquake. However, with the effect of Global Warming and changing in earth’s behaviours, the bridge should have resistance to withstand the effects of earthquake.

14 How could it have to be improved

Tsing Ma Bridge has been a great success. It has not only becomes an important link between the Hong Kong International Airport and Hong Kong mainland but also a landmark in Hong Kong. It was a great design to withstand the excessive wind and with a very good system to maintenance it. However, designed at least 15 years ago, therefore the techniques that were used was the new technique at the time. New material has developed during the last 10 years. If the main suspension cable was made out of new stronger material such as Fibre Reinforced Plastic (FRP) which is a stronger material than steel, the suspended span can be made longer. By making the suspended span longer, the man-made island on Ma Wan side did not needed to be constructed for the piers. Due to the high cost on the man-made island, if it was not constructed, the cost of the whole Tsing Ma Bridge would reduced by a significant amount.

Also, if the Tsing Ma Bridge is spanned from Sham Tseng instead of Tsing Yi, the main span over the channel (shown on Figure 16) could be made shorter and the man-made island does not needed to be built, so the diameter of the main suspension cable would reduced and the cost would also reduce significantly.

![Figure 16: Possible position of Tsing Ma Bridge](image)

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