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STRUCTURE INSPECTING AND MONITORING OF SUSPENSION BRIDGES

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ABSTRACT

In the early days, there are so many pedestrian suspension bridges in Taiwan because of its geographic surrounding with mountain and river valley. The inhabitants pass through the bridge from two separated areas over a long period of time with unknown danger because of incomplete maintenance. There are several types of non-destructive testing techniques like ground penetrating radar technique, penetrating test, radiation test, ultrasonic testing, magnetic testing…etc. evaluate the main components of the suspension bridge including steel hinge bearings, concrete pylons, and cables which didn't inspect for a long time in Bitan bridge. Also construct a structure health monitoring system with multi-type sensing technologies including analog and optical sensor to collect the response of the bridge to identify the motion behavior. User can easily modify the setting of the system and get the information of the in-situ bridge through the internet. The SHM system provides very useful information for safety evaluation and regular maintenance of the bridge under in-service condition.

KEYWORDS

Suspension bridge, non-destructive testing, structural health monitoring, structural health diagnosis.

INTRODUCTION

Suspension bridges were the most popular structure types in the early years. It provides some advantages like fast constructing, large span, fit any type of topography and most of all, it has special aesthetics of its appearance. (Lin 2008) However, many of the suspension bridges originally built for pedestrian, but with increasingly daring structures encompassing the experience and knowledge of structural designers, this fact has generated much stronger suspension bridges that allow cars passing through the bridges. Nowadays even changes their associated service ability from communication to tourism.

Most pedestrian suspension bridges didn't have its own managing authority to maintain it in Taiwan. Without systematic management, safety would not under control. In order to make changes in this situation, related units decided to take care of it and find some ways to solve the problems. Recently structure health monitoring systems are conducted to observe the behaviour of the bridges and construct numerical modal to analysis the critical conditions for early warning. We are still working on it due to the problem complexity. The loads are extremely complex and the structural system dynamic response, generally involves several vibration modes.

The pylons and main cables are the main components of the suspension bridge which take principally force, and the deck is fixed by the vertical cable. There are some disasters about suspension bridge in history that gives engineers some alert to recheck the design of the bridge. Tacoma Narrows Bridge in America collapsed in 1940 because of wind resonate to bridge. Recently Siringoringo and Fujino (2008a) did field experimental dynamic tests on suspension bridge as Yokohama Baysuspension bridge, Rainbowsuspension bridge, and Tsurumi Fairway cable stayed bridge to progress system identification. Siringoringo and Fujino (2008b), He(2009), Wang(2010), Yi(2010), and Brownjohn(2010) etc. all doing on-site experiment to get dynamic characteristics of the bridge and constructuring finite element model to analysis different kind of external loading acting on the bridge. With accurate numerical model can forecast the behavior of the bridge with various situations.

METHOD OF SOLUTION

Background

A dynamics-based methodology and inspecting technologies for the structural evaluation of historic structures was applied to the Bitan suspension footbridge (Figure 1). Getting realize the dynamics characteristic of historic structures to build up standards for future maintenance.

Figure 1. On-site Bitan suspension footbridge

Scheme

Preliminary visual inspection was made to quickly survey the overall condition of the bridge. There isn't any obvious structural crack on pylons and bearings. Inside inspecting is still necessary to confirm including fatigue crack of steel hinge bearings, inside defect inspecting, and pylon integrity examine, in the end, structure health monitoring system.
Human beings calculating system was set on the east and west entrance of the footbridge. And the number of people will deliver to the local working station nearby the footbridge. There is a LED electron bulletin provide safety guard to execute restrain when the tolerance capacity exceed. With camera also installing on both pylon, it can provide field situation to get further information.

Structure monitoring system constructing scheme involves a 2-axis inclinometers, concrete and cable thermograph, and wind monitor system on the top of the pylon. Structure vibration tests were conducted on the bridge using a 4-channel data optical fiber acquisition system with a total of 12 2D/3D FBG accelerometers installed on the lateral sides of the bridge. 2 sets of 3D FBG accelerometers are installed near the center of the bridge (Figure 2).

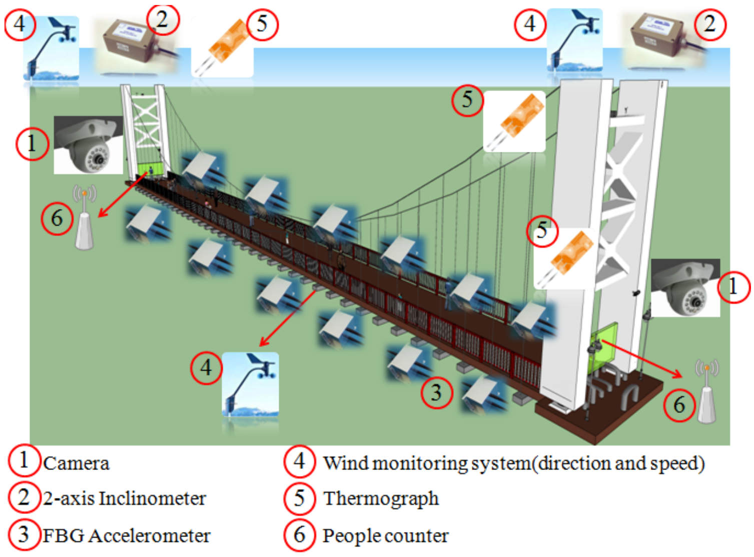
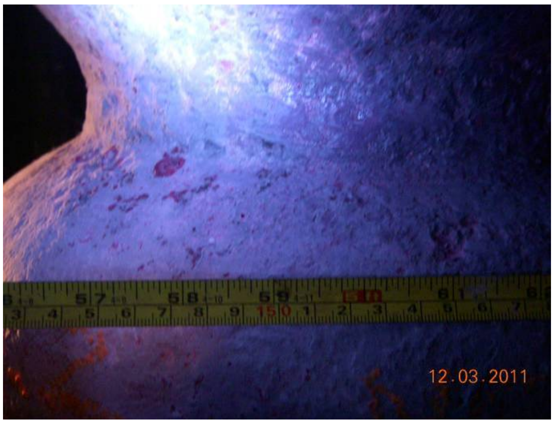


Figure 2. Structure health monitoring of footbridge

BRIDGE INSPECTING RESULT WITH NON-DESTRUCTIVE TESTING

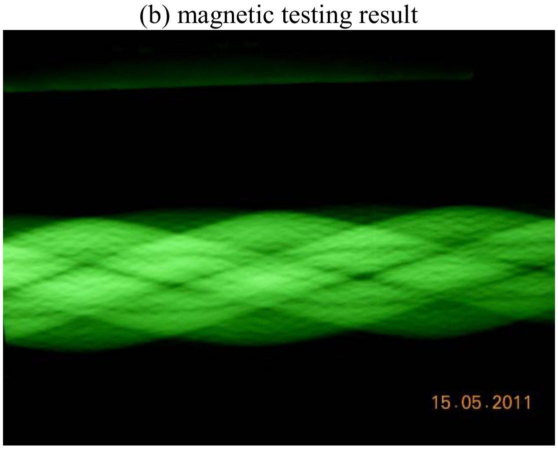
According to the reference, the saddle on the top of the pylon design fix end, and steel hinge bearing on the bottom. When horizontal or lateral force acting on the pylons, the hinge will rotate for balance. After using for a long time, there might have fatigue crack appear on the surface of the steel hinge bearing. This project applied penetrating testing (CNS 11225 1985), magnetic testing (CNS11377 1985) and ultrasonic testing (ASTM A388 1988) to the steel hinges (Figure 3). The penetrating testing result shows that the steel exist some caves and air holes. According to standard it classified as two level circular defects (2mm~4mm), and its fine with safety. The magnetic testing result find out a tiny crack on the bolt, it's still not dangerous. The ultrasonic testing can measure the thickness of the steel hinge bearing to check any material loss on it. The result shows that the thickness still match the original design. Above mentioned we can ensure the safety of the bearing that can still give service to on-site bridge. For cable inspecting, this project use radiation testing to identify the continuity. And based on the cable integrity standard, the cable can allow 7% section area loss or 10% necking effect. We choose the position top of the pylon cross the saddle with high potential stress concentration. Radioactive rays can penetrate the cable and imaging on the negative to find any defect inside the cable. Figure 1 shows there isn't any defect inside cable.



(a) penetrating testing result

(b) magnetic testing result

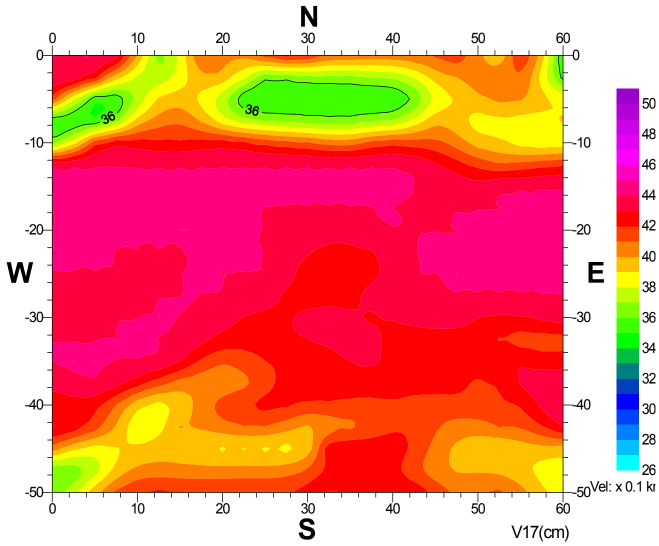
(c) ultrasonic testing



(d) radiation testing

Figure 3. Non-destructive evaluations for bearing and cables of suspension footbridge

This case use tomography inspecting techniques to identify the quality of the concrete of the pylons. Tomography refers to imaging by sections or sectioning, through the use of any kind of penetrating wave. A device used in tomography is called a tomograph, while the image produced is a tomogram. The inspecting processing using two detectors cross the section then using man-made impact wave passing through the section area. With various data can get inside velocity profile to check unusual area like Figure 4. Figure 4 shows that the green color zone was found that the velocity below 4000cm/sec, we can see that there exist spalling concrete.



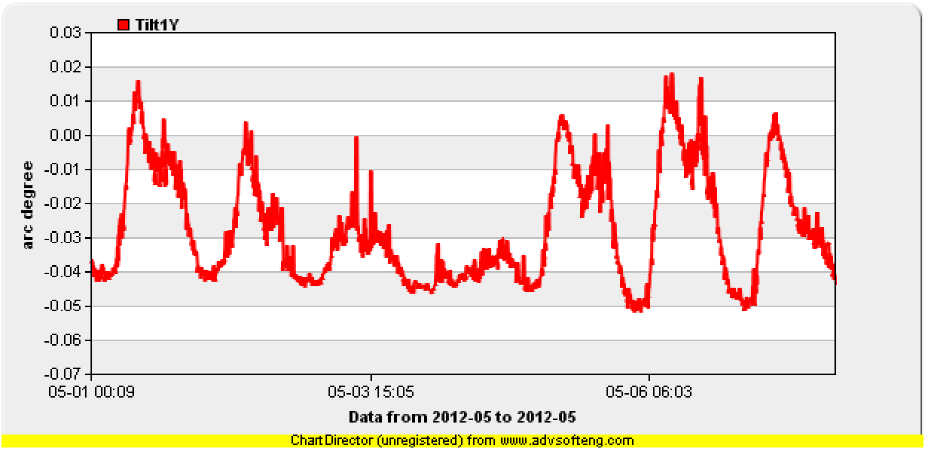
(a) Tomography techniques

(b)

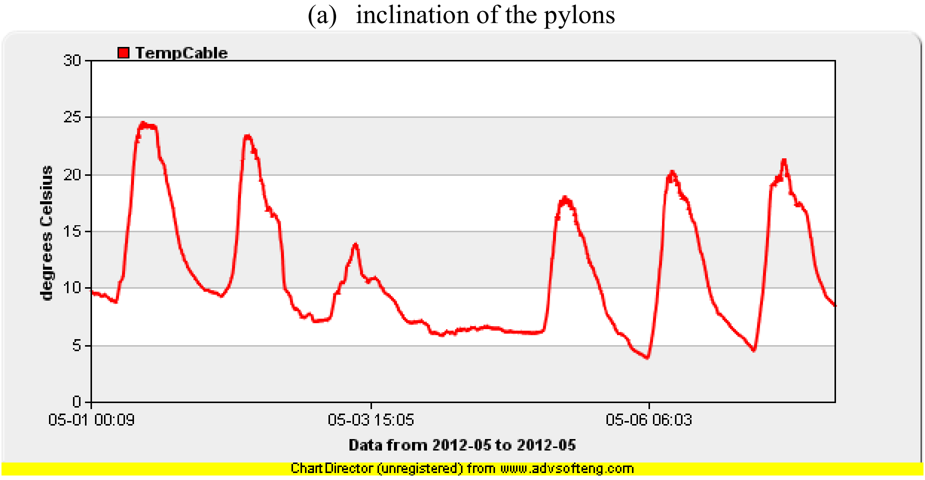
Figure 4. Non-destructive evaluation for pylons of suspension footbridge

STRUCTURE HEALTH MONITOURING SYSTEM

Based on derived data of monitoring system, the angle of inclination of the pylon is related to the temperature of main cable seen as Figure 5 When cable is heated with elongation, the pylons tilt inward to the bridge deck side. Otherwise pylons tilt outward with cable shortening.



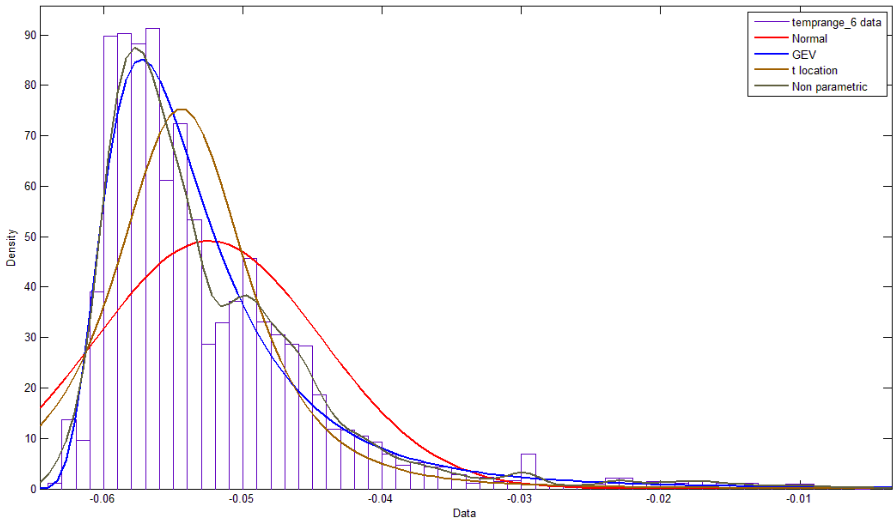
(a) inclination of the pylons



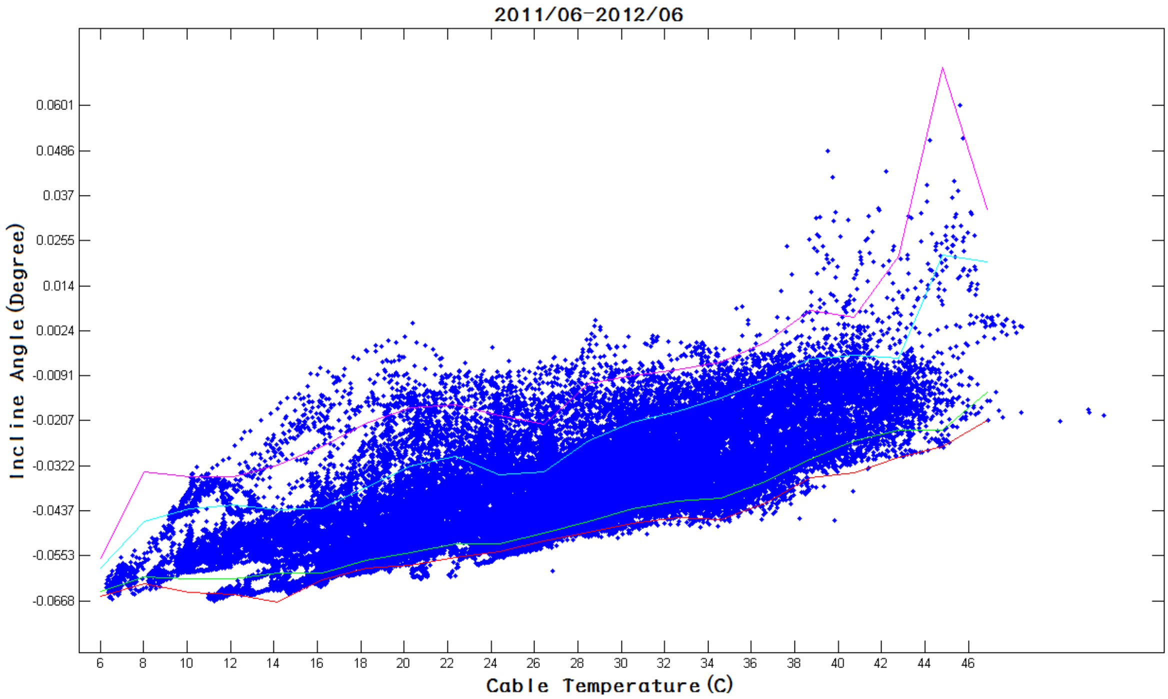
(b) temperature of main cable

Figure 5. Inclination of the pylons related to the temperature of main cable

Cable temperature is one of the important factors to affect inclining angle of pylon. There are some statistics methods to define warning vale of angle in varies temperature of main cables. The most important thing is to get the probability density function of derived data, and then based on the result to define the up-bound and low-bound curve. Here we set three times level of 95% confidence interval to define warning value of inclining angle (Figure 6).



(a) Probability density function of derived data



(b) Three times level of 95% confidence interval to define warning value of inclining angle

Figure 6. Warning vale of angle in varies temperature of main cables

DYNAMIC CHARACTERISTICS OF THE FOOTBRIDGE AND MODAL IDENTIFICATION

Operational modal analysis, i.e. the extraction of modal parameters (natural frequencies and mode shapes) from output experimental data. The modal identification has been carried out in the frequency domain using the Fast Fourier Transform Method and Peak Picking Spectral Method like stochastic subspace identification method to get main frequency of the structure seen as Figure 7. Then doing phase angle analysis to get the nature vibration mode of the bridge.

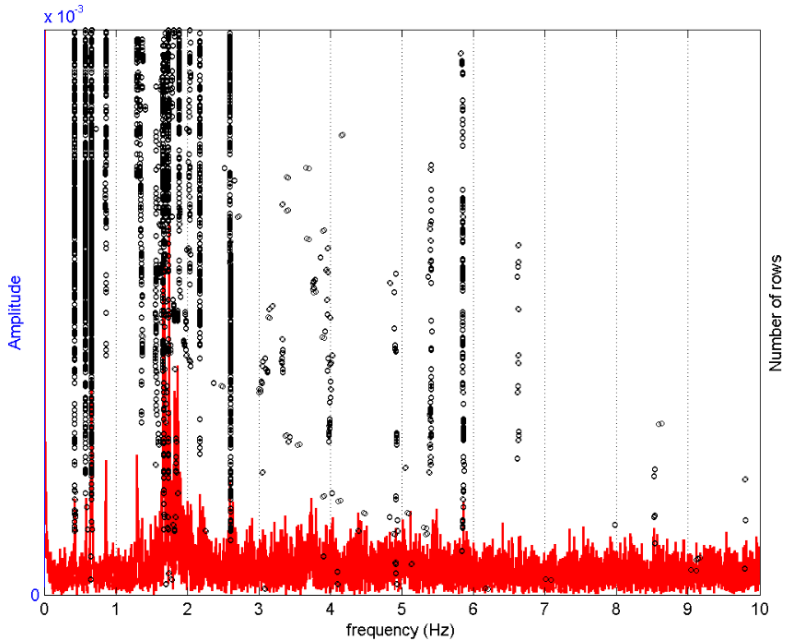
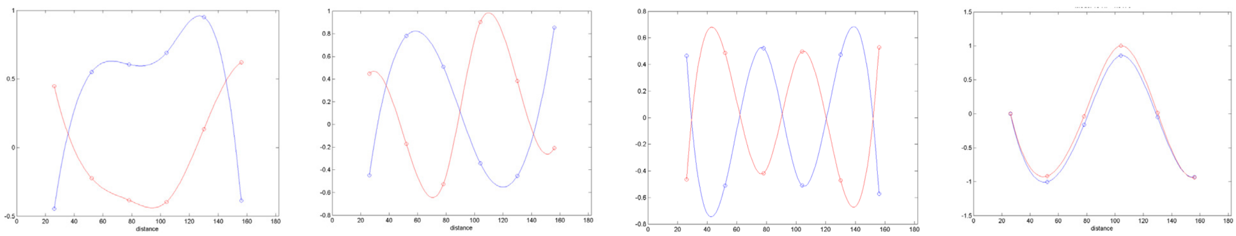


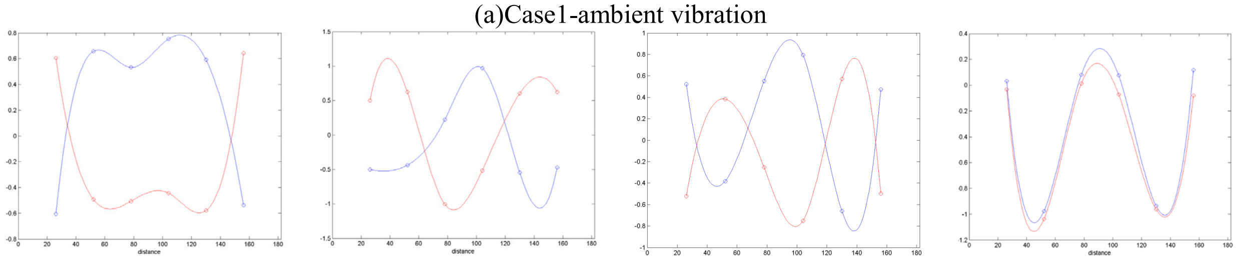
Figure 7. Modal identification in the frequency domain using the Fast Fourier Transform Method and Peak Picking Spectral Method

As previous stated, the operational modal identification was carried out by using FFT and PP techniques in the frequency domain. Modal analyses consider the vibration energy focus on the vertical direction. Compared with difference loading acting on the bridge, choosing two cases respectively ambient vibration (case1) and vibration due to vertical human loads(case2) to do modal analysis like Figure 8. In Figure8 shows that the blue line is the vibration modes of upstream deck, and the red line is the vibration modes of downstream.



Torsion 1-Mode 0.658 Hz	Torsion 2-Mode 0.856Hz	Torsion 3-Mode 1.746 Hz	Vertical 3-Mode 1.318Hz

(a)Case1-ambient vibration



Torsion 1-Mode 0.658 Hz	Torsion 2-Mode 0.869 Hz	Torsion 3-Mode 1.944 Hz	Vertical 3-Mode 1.461Hz

(b) Case2- vibration due to vertical human loads

Figure 8. Identified mode shapes

The identified modes can be classified as vertical bending modes and vertical torsion modes of the deck. Figure 8 shows the identified mode shapes: the first vertical torsion mode is one sin wave, with a frequency of 0.658 Hz.

With reasonable judgement, this project use force detective accelerometer to measure the vibration of bridge deck, it will occur couple effect so that each axis would not be independent. It induced extra energy for amplifying torsional signal instead of vertical signal. But its fine to proceed it because we know that suspension bridge both external loading and structure behavior are all complex. It will take lots of time to decompose each signal from different external factor. We just want to use fewer instruments to find critical condition of the footbridge for related authority in maintenance.

The experimental program of field tests was complemented by the development of a 3D FE model (Figure 9) based on the topographic survey of the dead-load deformed shape. Figure 7 shows that the midpoint deflection is larger than other position and the resisted wind cable occur local failure on one fourth and three fourth span seen as Figure 7. It means that world be the most possible position with cable limp.

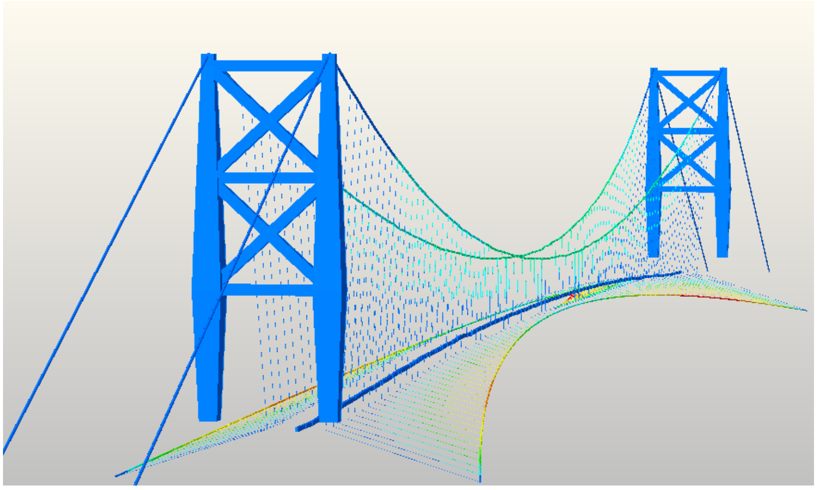


Figure 9. Numerical model constructed by MIDAS CIVIL software

CONCLUSIONS AND DISSCUSSION

This project applied several types of non-destructive testing instrument to proceed with safety evaluation of pedestrian suspension bridge. To identify any defects on sphere steel hinge bearing, penetrating testing, magnetic testing and ultrasonic testing was performed. Apply ground penetrating radar and tomography techniques to acquire inside conditions such as structure design or any defects of concrete pylons. Ensure main cables continuous with radiation testing. All inspecting results show that each inspecting techniques are imperative and the field test are totally successful. In the future, related organization could follow this procedure to execute structure health evaluation on each component of suspension bridge.

Except structure safety inspection, this research concludes some features of suspension footbridge via monitoring system and inspecting results. The pylons tilts inward and outward because of main cables extend and shorten. Here using statistics method to define warning value of inclining angle for preliminary safety criteria of Bitan suspension footbridge. Modal analysis to get main frequency and mode shape that can explain the behavior of the bridge deck. According to ISO-2631 standard even can comprehend the pedestrian's feeling according to the index from ISO-2631 standard. Finally numerical model is constructed for predicting complex external loadings acting on the bridge. This numerical still can't fit the on-site bridge, and still working on it that the new numerical software called VFIFE is considered. Since the model exhibit an excellent correlation with the experimental results, it can be concluded that the model provides an accurate representation of the actual footbridge and it can be used to evaluate the overall structural safety under the service loads and as the baseline model for long term monitoring.

Nowadays there are still many clapped-out pedestrian suspension bridges for tourism in Taiwan and no one knows the bridge is safe or not. In Taiwan it's the first time to carry out comprehensive inspecting and construct structure safety monitoring system especially for pedestrian suspension bridges. We are pleased to share this result to anyone who are interested and remind related maintenance organizations how importance the safety of the bridge is.

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