# Establishment and Initial In-Site Testing for the Structural Healthy Monitoring System of the Kinmen Bridge in Taiwan

CHIN-KUO HUANG, HSIN-CHU TSAI, LI-TING CHUNG
and CHIN-TE LIN

**ABSTRACT**

The newly-constructed Kinmen Bridge is the first cross-sea bridge for the daily commuting and medical support issues between Kinmen Island and Leiyu Island (so-called Little Kinmen Island) in Taiwan. In order to well understand the initial state and following operation conditions, a tailored-made structural healthy monitoring (SHM) system is suggested and established for the bridge. This article, in detail, describes the planning and installation of this SHM system, including cable tension force, structural behavior, and environmental monitoring, as shown in Figure 1. Subsequently, a series of onset structural condition tests on the bridge are triggered as the force inspection of cable tension, ambient testing, loading testing, and analysis of characteristics during both static and dynamic states. The experimental outcomes effectively optimize and calibrate the relative parameters and boundary conditions in the structural model of the bridge. It is expected that the following scenario simulation could provide predictions on pretension loss, temperature effect, overloading, and earthquake effect on this bridge in future. Moreover, the several critical thresholds in the calibrated numerical model could be settled, and contingent alarms will be in-time announced to the bridge management unit. This joint structural analysis and SHM-based in-situ testing could achieve the aim of real-time monitoring and diagnosis for the Kinmen Bridge.

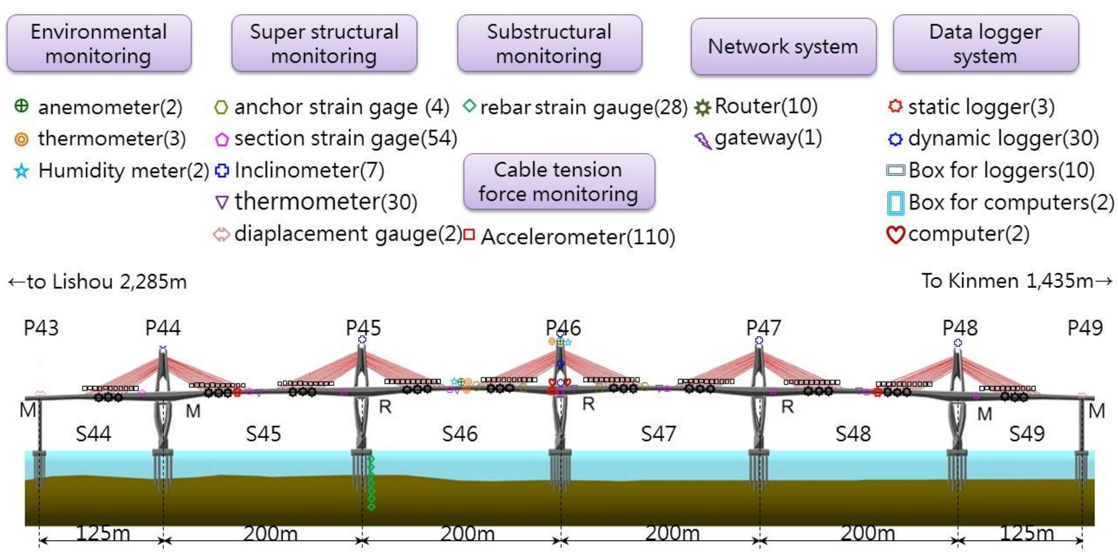


Figure 1. SHM system of the Kinmen Bridge

## INTRODUCTION

The newly-constructed Kinmen Bridge is the first cross-sea bridge for the daily commuting and medical support issues between Kinmen Island and Leiyu Island (so-called Little Kinmen Island) in Taiwan. The overall 5.414-kilometer length of the whole bridge construction consists of one 4.77-km-long bridge and two approaches. The key large-spanned extradosed bridge is designed as 5 sailing ship models crossing over the main channel. Its structural type consists of 5 concrete pylons and 6-span prestressed concrete box girders. The span allocation for the extradosed bridge is designed as 125 m+4@200 m+125 m, with a total length of 1,050 meters. The height of the five pylons is 78.5 meters above sea level and each side of a pylon is installed with 11 external prestressed tendons, with a total number of 110 tendons. Each pylon foundation is supported by varying from18 to 25 cate-in-place concrete piles, dependent upon the sea floor conditions. Each single 2.5-m-diameter full casing pile penetrates into the granite sea floor up to 24 meters deep, at least. The layout for the 18.8-meter-wide road is settled as two-way vehicle roads and mixing walkways and bikeways.

This paper describes the planning and installation results of the SHM system of the Kinmen Bridge and the implementation method of the field test. It describes instrument type and Specification for the SHM system and in-situ test. Through the establishment of SMH system and the implementation of in-situ tests (including ambient vibration, cable vibration modal testing, static loading test and dynamic loading test), the health data of the bridge at the early stage of completion are collected, which can be used as reference for the follow-up maintenance and management.

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Chin-Kuo Huang, Hsin-Chu Tsai, Li-Ting Chung, Chin-Te Lin, Facility Technology Center, China Engineering Consultants, Inc., 28F., No. 185, Sec. 2, Xinhai Rd., Taipei City 106213, Taiwan. Email: ckhuang@ceci.org.tw

### Structural health monitoring system for Kinmen bridge

The SHM system of Kinmen bridge consists two part: dynamic monitoring and static monitoring. The dynamic monitoring is mainly for the cable tension force, while the static monitoring is mainly for the bridge structure and site environment.

### Monitoring system for cable tension force

There are 5 pylons in the main section of the Kinmen Bridge, and each tower has 2 sectors, totaling 10 sectors. Since each sector has 11 bundles of cables, 110 bundles in total, each bundle of cables is installed with a uniaxial force balancing accelerometer. However, the length of the main section of the Kinmen Bridge is 1,050 meters. In order to avoid excessive signal line length, one cable force monitoring box is set up for each cable sector. There are 10 cable force monitoring boxes in total, and three four-channel dynamic data loggers are set up in each cable force monitoring box. The vibration acceleration response of cable is mainly monitored, and the sampling rate of 100samples/sec is used to capture the vibration acceleration response of cable. Every 5 minutes of data is recorded, spectrum analysis is automatically conducted to obtain its modal frequency. Combined with the results of vibration mode detection test of cable, the dual-frequency method [1] is used to conduct real-time calculation of cable tension. The specifications of the instruments and equipment are shown in Table I.

**Monitoring system for bridge structure**

There are 5 towers, 6 spans and 2 expansion joints in the main bridge section of the Kinmen Bridge. The static SHM system mainly monitors the bi-directional tilt Angle of each tower, 9 cross sections in the box girder, the strain and temperature of the top plate, outer web and bottom plate of the left hand-side box and right hand-side box chambers, as well as the longitudinal displacement of the expansion joints at both ends. In addition, the concrete anchoring blocks of the longest and shortest four strands of cables of the intermediate bridge pylons are selected for strain monitoring. This system uses 3 static system monitoring boxes, each box is installed with 1 static data logger and a different number of channel adapter boxes, which are respectively located in the right hand-side of the box girder of the second, third and fifth span of the main bridge. The specifications of the instruments and equipment are shown in Table I and the photos are shown in Figure 2(c)~(f).

**Monitoring System for Environment**

In order to understand the impact of environmental changes on the monitoring data of the Kinmen Bridge, an environmental monitoring system was also set up, including the monitoring of wind speed, wind direction, humidity and temperature at the top of bridge tower and bridge deck, as well as the temperature change inside one box girder. Environmental monitoring data is also received through static data logger. The specifications of the instruments and equipment are shown in Table I, and the photos are shown in Figure 2(f)~(g).

TABLE I. INSTRUMENTS OF BRIDGE MONITORING SYSTEM

| System | Item | Company | Model | Specification | Numbers |
|---|---|---|---|---|---|
| Cable tension force | Uniaxial Force Balance Accelerometer | Sara | SA-10D | Range:±2g<br>Dynamic Range:165dB | 110 |
| | Dynamic data logger | Sanlien | DMS-24 | Channels:4<br>Resolution:24bits | 10 |
| Static (Structural and Environment) | Inclinometer | RST Instruments Ltd. | IC6654 | Range:±10°<br>Resolution:0.01° | 7 |
| | Vibrating wire strain gage | RST Instruments Ltd. | VWSG-E | Range:3,000 $\mu\varepsilon$<br>Sensitivity:1 $\mu\varepsilon$ | 66 |
| | Thermometer | HOLI Enterprise Co., Ltd. | PT100 | Range:0℃~100℃<br>Resolution:0.2℃ | 33 |
| | Anemometer | Campbell Scientific, Inc. | 05103 | Wind speed:<br>Range:0~100m/s<br>Accuracy:±0.3 m/s<br>Wind Direction:<br>Range:0°~360°<br>Accuracy:±3° | 2 |
| | Humidity meter | Vaisala | HMP155 | Range:0~100%RH<br>Accuracy:±1%RH | 2 |
| | Static data logger | Campbell Scientific, Inc. | CR1000X | Channels:4<br>Resolution:16bits | 3 |

**Central Controller System and Network System**

Because the span of the Kinmen Bridge is as long as 200 meters, in order to avoid the delay of monitoring data transmission, the transmission mode of the general RJ45 network route is abandoned, and optical fiber transmission is adopted. Each cable force monitoring box is connected in series through optical fiber and managed gigabit Ethernet switch. And in the first cable force monitoring box and the 10th steel cable force monitoring box string up a backup optical fiber line at least 800 meters long, to ensure that in case of interruption of one section of the optical fiber, there is another loop to ensure that the data transmission is not interrupted. The data transmission in the box girder is also connected by optical fiber, only the 2 computers of the central control system use the general RJ45 network route, in order to avoid a large number of data calculation and storage may lead to the collapse of the computer operating system, so the 2 computers are divided into processing cable force monitoring data and static monitoring data two parts, and to avoid a sudden interruption of power, may lead to computer abnormalities, The UPS is installed to maintain stable power. After the on-site monitoring is stored and calculated at the computer, the calculated data is sent to the cloud server through the 4G mobile network gateway for storage and display on the monitoring web page. The specifications of the equipment are shown in Table II, and the photos are shown in Figure 2(h)~(i).

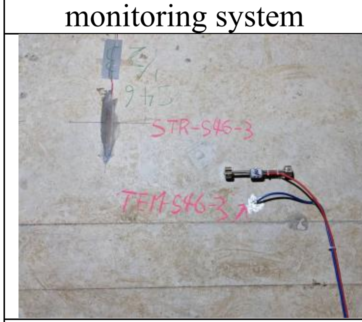
TABLE II. CENTRAL CONTROLLER AND NETWORK SYSTEM

| Item | Company | Model | Specification | Numbers |
|---|---|---|---|---|
| Industrial Computer | Advantech Co., Ltd. | ARK-1551 | CUP:Intel i5-8365UE 1.6GHz, 4 Core<br>RAM:16GB DDR4 2400MHz<br>OS:WIN10 IOT | 2 |
| UPS | ideal | 9303LB | Capacity:3KVA/2400W<br>Voltage:220V | 2 |
| Industrial cellular gateway | Moxa Inc. | Oncell G3470A-LTE | Cellular Standards: GSM, GPRS, EDGE, UMTS, HSPA, LTE CAT-3<br>Total Port Count:4 | 1 |
| Managed Gigabit Ethernet switch | Moxa Inc. | EDS-510E | RJ45 connector:7<br>Combo Ports:3 | 10 |
| SFP module | Moxa Inc. | SFP-1GLXLC-T | Ports:1<br>Connectors: Duplex LC connector | 22 |

(a) box for cable monitoring system

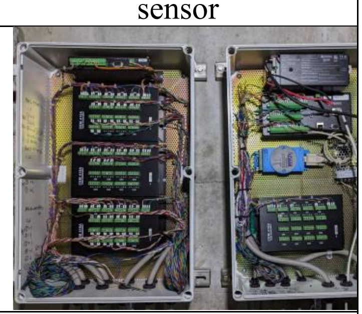
(b) uniaxial force balance accelerometer

(c) Biaxial tiltmeter sensor




(d) Vibrating wire strain gauge & thermometer

(e) Draw-wire displacement sensors



(f) box for static monitoring system

(g) Anemometer & humidity meter

(h) box for central controller computer

(i) UPS

Figure 2. SHM system for Kinmen bridge

## IN-SITE TESTING

In order to establish the basic health data table of the Kinmen Bridge at the initial stage of completion, which can be used as a reference for the follow-up tracking of bridge health changes, the ambient vibration test, cable modal detection test, static loading test, dynamic loading test, such as large in-situ bridge tests were carried out. Relevant test execution methods and measurement contents are described as follows:

### Ambient Vibration Test for Bridge

There are six spans in the main section of the Kinmen Bridge. Except for the two side spans which are 125 meters long, the rest main spans are 200 meters long. In this paper, the modal shapes and frequencies of the six spans are obtained by ambient vibration test by span to span and overlapping points are set. Five triaxial velocity sensors were used on each span and installed at equal intervals. The sampling rate was 1,000 samples/sec and the recording time length was 15 minutes. The triaxial velocity sensor used was MST-1031 which produced in Switzerland, and the dynamic data extractors were NI cDAQ-9185 and NI 9224 produced in the United States. The specifications of the instruments were shown in Table III, and the test performance was shown in Figure 3(a).

### Cable Modal Detection Testing

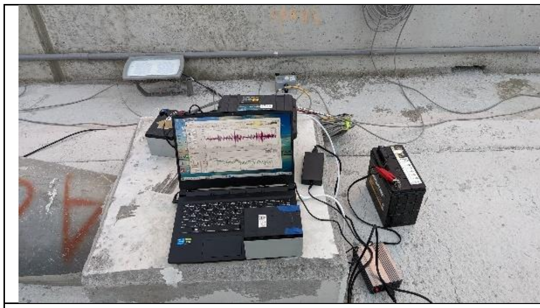
There are 5 pylons in the main section of the Kinmen Bridge with 110 bundles of cables. In order to obtain the modal frequency, effective vibration length and cable tension of the cables at the initial stage of completion, the cable modal detection test is carried out. The test execution method is to lay 5 triaxial velocity sensors on the cables one by one, and considering that the length of the steel cables is between 45 meters and 95 meters, the 3+2 layout method is adopted. That is, three triaxial velocity sensors were set up near the anchoring end of the bridge deck at equal intervals, and two triaxial velocity sensors were set up near the anchoring end of the bridge pylon. The sampling rate was 1,000 samples/sec and the recording time length was 15 minutes. The instruments and equipment used were the same as the ambient vibration test, and the test execution was shown in Figure 3(b). In the subsequent signal analysis, spectrum analysis and modal shape fitting will be used to obtain the cable modal frequency and effective vibration length, and the cable tension will be calculated with equivalent simply supported tension beam method [2-3]. The cable modal detection testing was just completed on February 23th.

**Static Loading Test**

In order to obtain the real response of the 6 spans in the main section of the Kinmen Bridge under the known loading weight, static loading test was carried out. The execution method was to use 10 trucks with about 25 tons to carry out loading at the mid-span of each span, and to measure the level elevation, the internal cross section strain of the box girder and the vibration velocity of the bridge girder during the static loading testing. The variation of vertical deflection, section strain and vibration frequency of the bridge. During static load test, Leica Sprinter 350M electronic level is used to measure the level elevation. KYOWA resistance strain gauge from Japan is used for section strain response measurement, and it is equipped with CRFX-2000 dynamic data logger produced by IMC in Germany. See Table 4 for details of instrument specifications. The equipment used for vibration measurement is the same as that used for ambient vibration testing, and the test execution is shown in Figure 3(c)~(e). The static loading test was just completed on April 22th.

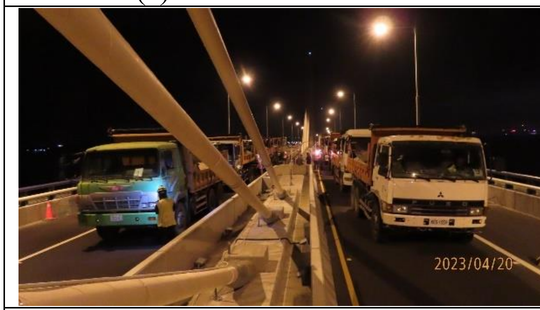
**Dynamic Loading Test**

Considering the ambient vibration test, it is usually difficult to obtain the modal above the second order of the bridge, and in order to understand the impact effect on the bridge under the condition of constant speed of the vehicle with known loading weight, dynamic loading test is carried out to obtain the modal above the second order and the dynamic impact coefficient. The implementation method is to measure the bridge with three different weights of 19 tons, 25 tons and 35 tons respectively at a speed of about 60km/hr, and record the section strain and bridge vibration during the passage of the trucks. Dynamic loading test adopts the same strain measurement and vibration measurement equipment as static loading test, and the test execution is shown in Figure 3(e)~(f). The static loading test was just completed on April 27th.



(a) Ambient vibration

(b) Modal inspection of cable




(c) Static loading test(truck)

(d) Static loading test(leveling surveying)

(e) loading test(strain of concrete)

(f) dynamic loading test(tractor trailer)

Figure 3. In-situ testing of Kinmen bridge

TABLE III. MEASUREMENT INSTRUMENT FOR IN-SITU TESTING

| Item | Company | Model | Specification | Numbers |
|---|---|---|---|---|
| Dynamic datalogger | National Instruments | cDAQ-9185 NI 9224 | Channels:16<br>Resolution:24bits | 2 |
| Dynamic datalogger | Imc Test & Measurement GmbH | CRFX-2000 | Channels:48(8ch/module)<br>Resolution:24bits | 6 |
| Analog tri-axial velocity sensor | Walesch Electronic GmbH | MST-1031 | Frequency range:1~315 Hz<br>Measuring range:1、10、100mm/s<br>Sensitivity:10、1、0.1V/mms/、 | 5 |
| Strain gage | Kyowa | KC-120-120-A1-11 | Gage Factor:2.07±1%<br>Gage Length:120mm | 168 |

## STRUCTURAL ANALYSIS MODEL

This model adopts Midas Civil to build a structural analysis model according to the design drawing of the Kinmen Bridge, in which a total of 989 nodes, 845 members, 7 bottom boundary conditions of piers, 6 supporting conditions Settings, 674 internal prestressed tendons and 110 external prestressed cables are established, and the longitudinal curve and transverse curve of the bridge is established by referring to the design elevation and curve, as shown in Figure 4.

### Material Parameters and Member Define

Materials of superstructure and substructure of the bridge are concrete. The compressive strength of the superstructure is f 'c = 420 kgf/cm$^2$, while the compressive strength of the substructure is f 'c = 350 kgf/cm$^2$, both of superstructure and substructure were simulated by beam element. The cable system has the corresponding cable with 55T-15.2mm$\varphi$ and 43T-15.2mm$\varphi$, and the structural model uses the truss element to simulate the cables, and apply initial prestressed force.

### Cross Section Type

The main girder is a three-box prestressed concrete box girder. It’s section depth varies from 3.3m to 7m, while the section of the pylon and pier varies nonlinear with the change of height.

### Definition of boundary condition

In the model, Elastic Link was used to simulate the support at the connection between the superstructure and the substructure. The most left and most right piers were connected to the superstructure by bi-directional pot bearing and the transverse force was transferred by shear steel boxes. The remaining three central piers were connected to the super structure by rigid connection. The point spring is used at the bottom of the pier, and input the stiffness of basement into the structure mode, so as to simulate the stiffness of the basement in all directions.

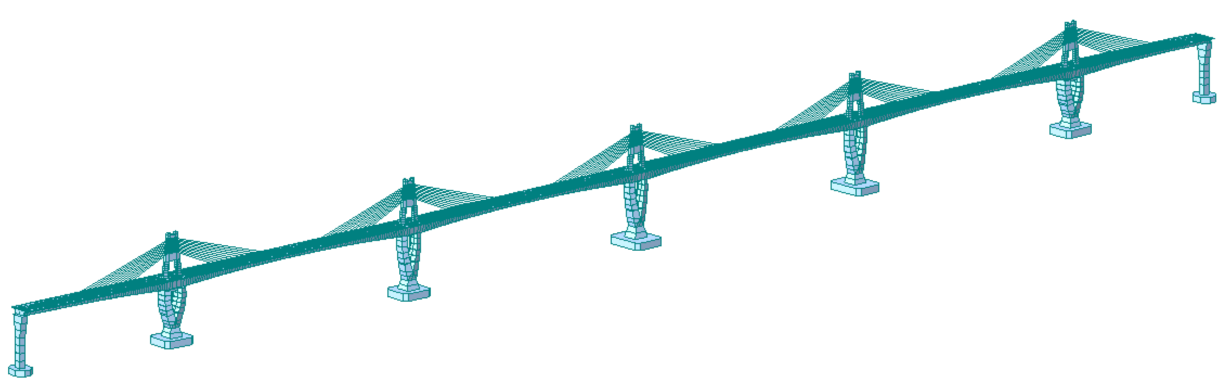


Figure 4. Structural analysis model of Kinmen bridge

## CONCLUDING REMARKS

Through this in-situ testing, the actual responses of the Kinmen bridge was collected. Based on these in-situ test results, the initial value of the health resume of the Kinmen Bridge will be established as a reference for future management units for track and compare. Subsequent analysis, comparison and discussion will be conducted based on the measured data, so as to further understand the changing characteristics of the Kinmen Bridge under the known loading weight. Through the analysis of the experimental results, the existing structural analysis model will be further adjusted to make the structural analysis model more similar to the real situation of the bridge, which can be used as a reference for future situation simulation and monitoring and management.

## REFERENCES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