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CRACKING OF STEEL GIRDER OF THE VAM CONG BRIDGE - THE INCIDENT CAN BE AVOIDED DURING THE CONSTRUCTION STAGE

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ABSTRACT: Vam Cong cable-stayed Bridge which has a 450m main span length, is one of the Central Mekong Delta Region Connectivity Project and is located in Cuu Long Delta Region. It has a steel-concrete composite girder with four lanes, and the type of cable is a multi-strand cable. Cables support a cable-stayed bridge, and the negative reaction occurs by cables at the anchor pier. On November 14, 2017, during the construction of expansion joints at the P29 pillar, the contractor had discovered the CB6 cross beam to be cracked. The tear is more than 4 cm wide, extending about 2 m across the beam. In this article, the author will determine the exact location of the damage, analyze the factors and causes leading to the above damage. At the same time, it points out the errors in the construction process, especially in the monitoring process of the bridge during the construction phase. This can help to identify the phenomenon that has led to this severe damage early.

Keywords: Vam Cong cable-stayed bridge, Cracks, SHM system, Acoustic Emission

1. INTRODUCTION

Vam Cong is the second cable-stayed bridge over the Hau river (after the Can Tho bridge). The bridge connected Can Tho province and Dong Thap province with a total length is 2,969,4m. The main bridge is two planes cable-stayed bridge with three spans with composite steel girder length 870m (210+450+210) m. The tower is H-shape resting on a D2500mm bored pile foundation. Its height is 130,9m from pile cap to the top of the tower, is 110m from deck to top of the tower, respectively. The bridge is designed with four lanes and two rudimentary lanes, a design speed of 80 km/h, a navigable height of 37.5 m. The bridge deck is 25.8m wide, including two composite girders linked together by the cross beams; the distance between them is 4.0m (Fig. 1).

The bridge is designed with fan-shaped cable-stayed cables, including 114 wires arranged on two oblique planes. The approach bridge leading to Dong Thap includes 28 spans, while the bridge leading to Can Tho has 25 spans with Super T girder rests on a D1500mm bored pile foundation. Thus, the bridge has connected the center of the Mekong Delta, 5.75 km long (2.97 km bridge part). The Vam Cong bridge is the main component of this project [1].

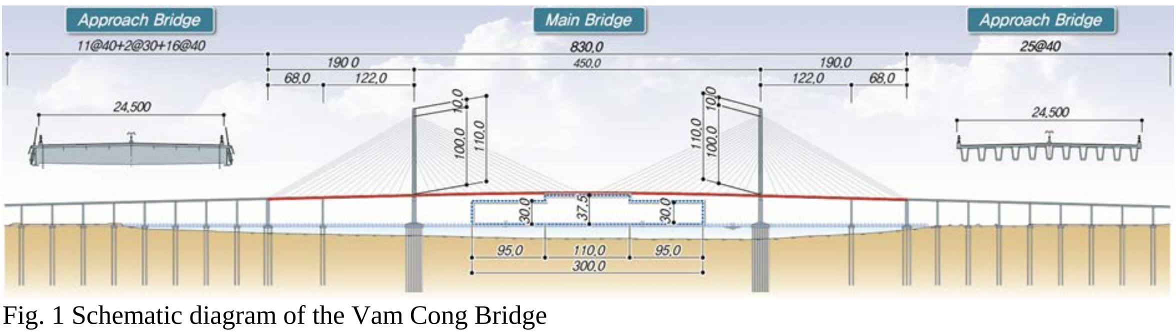

Fig. 1 Schematic diagram of the Vam Cong Bridge

On the afternoon of November 14, 2017, during the construction of the expansion joint at the P29 pillar, the contractor discovered that the CB6 horizontal beam was cracked. The tear is more than 4 cm wide, extending about 2 m across the cross-beam. Therefore, the Ministry of Transport has directed to immediately take necessary measures to ensure the stability of the work. Furthermore, the monitoring and monitoring of the technical condition of the bridge are carried out regularly to ensure the safety of the works (Fig. 2).

However, the fact that such a large and complex bridge project encountered a cracking problem - with a crack of more than 4 cm wide, about 2m across the girder during the construction phase, has not been affected by the live load. Nevertheless, mining is a severe problem, especially with steel structures. In this article, the author will study and analyze the factors and causes leading to this phenomenon.

Fig. 2 The tear in the beam CB6 pier P29 of the Vam Cong bridge is more than 4 cm wide, extending about 2 m across the cross-beam.

2. RESEARCH SIGNIFICANCE

In this article, the author will determine the exact location of the damage, analyze the factors and causes leading to the above damage. At the same time, it points out the errors in the construction process, especially in the monitoring of the bridge during the construction phase. Therefore, it can help with early recognition of the phenomenon that leads to this severe damage. Moreover, it allows drawing from future experiences so as not to repeat similar events. In addition, the author also proposes to add in the monitoring system of the bridge the solution of monitoring by acoustic emission technology, an advantageous method in early damage detection.

3. ANALYSIS OF FACTORS AND CRACKING PHENOMENON OF STEEL CROSS-BEAMS

3.1. The Official Evaluation Analysis

Immediately after detecting the crack of the Vam Cong bridge in November 2017, the Ministry of Transport has carried out an independent inspection and assessment. The Ministry also coordinates with the State Council for Acceptance of Construction Works and leads experts in assessing causes and selecting solutions. As a result, there are three reasons for cracking CB6 steel beams on top of P29 piers of the Vam Cong bridge, determined as stress concentration, residual stress, and quality of weld seams connecting components construction site combining and assembling beam horizontal CB6.

Because the cable-stayed bridge is symmetrical, when the CB6 cross beam at the top of the P29 anchor post is cracked, the horizontal beam on the top of the P28 pier on the other side is also affected, cracking at a slight degree. Therefore, the repair must be carried out simultaneously with both beams on the top of the piers P28 and P29 to ensure the quality and life of the bridge.

In principle, when heating to weld steel beams, there will be specific effects due to sudden temperature changes in the structure, so the welding process has stringent technical regulations. All steel products are imported from Korea, carefully checked by the main contractor, supervision consultant.

When manufacturing beam assemblies in the field, residual stresses are generated during welding. Some dangerous mechanical analysis experiments of the material, metallurgical engineering analysis will continue to be performed during the remediation process to determine the cracking mechanism. To date, independent tests and tests have shown that there is only local cracking on the CB6 transverse beam at the top of the P29 pillar. The cross-beam is assembled in the field from the blocks, and the assembly process at the construction site can also cause cracking after the fusion of the bridge.

Fig. 3 The tear at CB6 girder of the Vam Cong bridge.

Based on the verification results of the international consultant Arup, the Institute of Transportation Science and Technology, and the opinions of the State Acceptance Council, the proposed repair plan is to replace 60% of the steel cross-beam area. Replace all new wind vanes. The thickness of the bottom plate will be increased from 6cm to 8 cm to increase the stiffness of the beam.

The Korean contractor GS E&C has mobilized materials, equipment, and skilled workers from Korea. In addition, the welding cabins at the site are installed to ensure the same welding conditions as in the factory to accelerate construction progress.

3.2. Independent Evaluation Analysis

Based on studying the bridge's design drawings, the crack is positioned at the cross-beam near anchoring the two ends of the beam to the cross-beam of the anchor pillar. The anchor post is rigidly linked to the bridge deck. This helps to withstand the pull force at the anchor span. In addition, the internal residual cable connects the anchor post to the deck, ensuring the seamlessness between the deck and the pier. The anchor post consists of two rectangular hollow columns with a cross-section of 5.0m x 6.0m. There are many advantages in maintenance since the anchor cable is protected in the column. The column pier is placed on 27 bored piles with a diameter of Ø 1,500mm, a length of about 73 ÷ 80m. Two piers' pillars are placed on the river on either side of the pylon. These piers have been designed to withstand the collision loads caused by ships up to 1,000 DWT [1].

At this position, there is usually a pull force at both ends of the horizontal beam. The possibilities for this phenomenon are typically due to the quality of the material: inappropriate material plus dynamic load effects (sudden impact of wind, storms on cable-stayed cables) or too brittle steel material (steel with high carbon content) should not meet the standard of elasticity (Fig. 4).

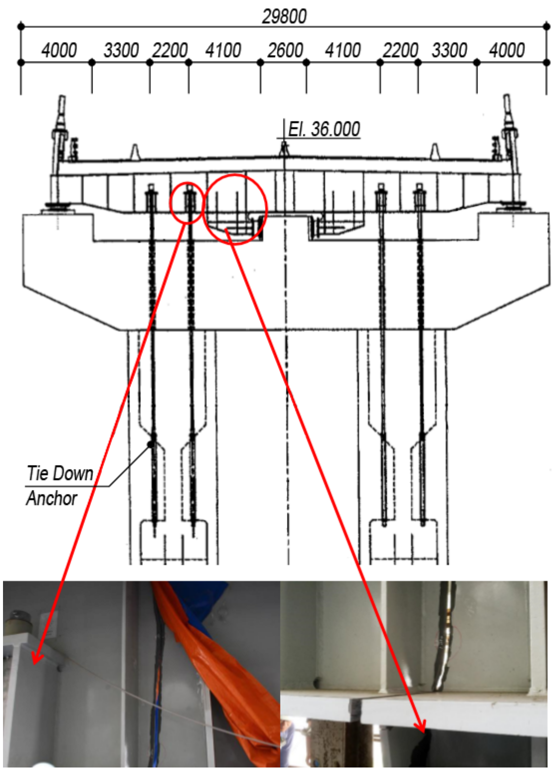

Fig. 4. Damage location in the cross-beam of the pier P29.

The working mechanism of the most extended cable to the anchor is shown in Fig. 5 and Fig. 6 [2].

Figure 4 shows that the nearest weld seam is about 5 cm from the crack and the size is very small because it is just reinforced tendon welding. Therefore, the heating amount of the weld is small, and if it is said that the crack is due to the quality of the weld, it must originate from the weld toe, or the weld is completely slipped or peeled case the weld is still intact. The crack runs almost along the weld. Therefore, weld seam quality in the structure in the unloaded state is negligible, not the main cause of steel beam cracking. For the damage shown in Fig. 3 to be possible, it would take a massive force in opposite directions to lead to the tearing of a steel cross-beam like a sheet of paper.

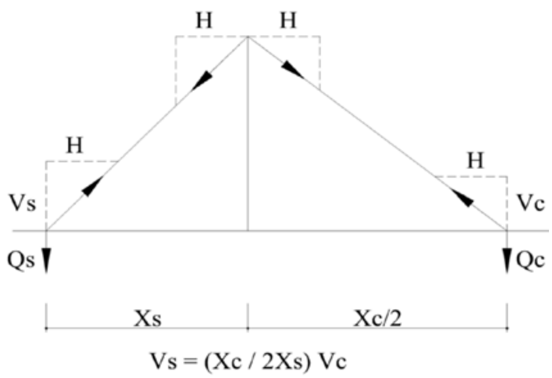

Fig. 5 Vertical force on the anchor cable

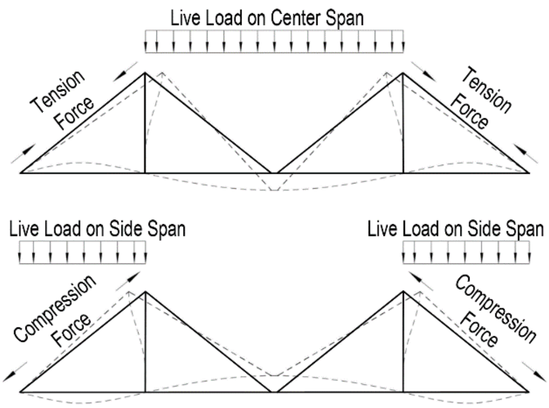

Fig. 6 Alternating force on the anchor cable

With cracks like this, the main cause is due to residual stress plus the quality of composite beams with high carbon content. When welding steel plates into cross beams at the field will generate huge residual stress. The tensile and extrusion of residual stress will destroy the beam.

One of the causes can be a design error. The crack extending from the bottom shows that the lower fiber of the cross-beam is subjected to substantial tensile stress, much larger than the strength limit, leading to the failure of the material. The CB6 beams on the two anchor piers P28 and P29 are cracked, so they have the same cause. In addition, these two beams are located at the outermost position where the most extended cable stays are. Therefore, it is necessary to re-examine the design of these two beams. Their design must be different from other beams inside the bridge. The location of the crack at the end of the girder where it is placed on the pier indicates that the upward force exceeds the load capacity of the beam. With the cable-stayed bridge structure, the force is evenly distributed on the girder through the slings. Still, it may be due to the wrong design or the large deformation of the beam when hanging, so the large distributed load on the beam head position exceeds the bearing capacity.

The welding technique of beams can also be one of the causes of damage to beams during construction. It is possible that in the design process, the selected load combination is not reasonable, plus the welding technology causes pre-heat deformation or creasing after being placed on the load and thermal deformation, sudden failure. From the picture (Fig. 2 and Fig. 3), the two vertical ribs are welded close to each other, so the prestress between these two ribs are likely to be very large. The horizontal welded beam blades usually have to be side-welded and full penetration welding. They must be checked by quality control 100% UT (Ultrasonic Testing) and 100% RT (Radiographic Testing) to ensure the quality of this beam, and butt-weld is likely to have been made not according to specifications [3].

Fig. 7 Cable-stayed tension control during cable tensioning by VSL experts and engineers

One of the other possible causes of damage, as mentioned above, is that the movable bearing. The bridge bearing at the pier P29 does not reserve enough displacement. The installation position has not been calculated correctly, so when the beam shrinks due to the tensile temperature, the beam rupture at a place near bearing P29. Moveable bearings come in many varieties and require pre-setting of displacement during installation. Usually, one of two bearings will allow horizontal displacement. But if there is a problem of longitudinal displacement, failure will occur at the bearing. As shown in Fig. 4 at the P29 pier (tier down pier), the mooring bundles are spaced very close to each other, proving that the bridge is designed to work under huge asymmetrical loads. At bearing P29, the displacements are longitudinal or transverse and twisted due to thermal expansion or uneven working of the most extended cable, resulting in unequal cable tension on both sides.

However, because the expansion joint is designed here, the longitudinal force generated by the anchor cable does not pass through the longitudinal beam behind the P29 pier. In addition, the expansion joint is located at the P29 pier, so the longitudinal beam facing the river must be calculated as the attachment to the P29 pier to transmit all the cable tension to the pier in the working state to allow displacement along the bridge. This can lead to cracking of the transverse beam near the attachment connected to the P29 post due to the involvement of the anchor cable in tension.

Based on the above analysis, the failure in the pier tier-down P29 is sudden cracking. The following reasons can cause this damage:

- Inappropriate structural design;
- Steel material is too brittle;
- The design of the combination of loads is not suitable for a real condition;
- Process of the manufacturing beams not following regulations;
- Transporting and assembling beams;
- Deformation after construction of the bridge deck (loading, thermal deformation of the deck).

However, the above factors can be partially eliminated or detected early if the bridge monitoring system during construction is installed and operated correctly according to design requirements. In section 4, the author will analyze the design of the monitoring system for the Vam Cong bridge and point out the flaws of this system during the bridge construction stage.

4. BRIDGE MONITORING DURING CONSTRUCTION STAGE

4.1. SHM System of the Vam Cong Bridge

4.1.1. Measurement strategies

Monitoring criteria are required for the efficient management of the SHM system and assessment of structural conditions. The monitoring criteria shall be determined considering structural analysis results, design documents, and environmental conditions. When evaluating the structural behavior using monitoring criteria, absolute value analysis and trend analysis based on measurement data shall be conducted. Monitoring criteria shall be provided for each sensor ahead of the establishment of the SHM system and determined through the discussions between Contractors and Engineers. Monitoring criteria shall be provided in different levels for Safe, Caution, and Warning. For each evaluation level, the appropriate plans and solutions shall be established as follows. In case of abnormal levels such as caution and warning, SMS or e-mail shall be sent to the management agent (Table 1) [4].

Table 1. Phased plan of Vam Cong bridge SHMS

Level	Measurement objectives
Level 1 [5] (safe)	Measurement data within maintenance threshold - Monitoring
Level 2 (caution)	Measurement data exceeding caution threshold - Forced storage of measurement data - Measurement system inspection - Data analysis and investigation of causes - Inspection of the relevant member
Level 3 (warning)	Measurement data exceeding warning threshold - Forced storage of measurement data - Measurement system inspection - Data analysis and investigation of causes - Structure inspection and evaluate the use of bridge

Vam Cong bridge is a long-span steel composite cable-stayed bridge, and the prominent structural members of the bridge are pylon, cable, and girder. Therefore, most sensors shall be arranged in the pylon, cable, and girder [6].

Pylon

- A strain meter shall be installed to monitor the stress intensity in pylon induced by cable tension.
- GPS shall be installed to assess the verticality and shape of the pylon.
- A multi-dimensional Shape (MDS) sensor shall be installed to evaluate the shape of the pylon.
- An accelerometer shall be installed to assess the vibration characteristics induced by live load and wind loads.
- A thermometer shall be installed to assess the thermal behavior of the pylon.

Cable

- An accelerometer shall be installed to indirectly calculate the cable force and evaluate the cable's dynamic characteristics.
- Load cell shall be installed to measure the tension of the tie-down cable.
- A Dummy cable shall be installed separately, and a thermometer shall be installed in the dummy cable to evaluate the thermal effect on the cable.
- If necessary, the separate device of portable cable force measurement shall be utilized.

Steel girder

- GPS shall be installed to measure the displacement of the steel girder.
- A strain meter shall be installed to measure the stress of the steel girder.
- An accelerometer shall be installed to assess the vibration characteristics of the steel girder.
- A thermometer shall be installed to evaluate the thermal effect on the steel girder.

Traffic/Climate conditions

- An intelligent camera shall automatically recognize the traffic flow and accidental event using image processing technology.
- A water-level camera shall be installed to evaluate the water level in real-time by using image processing technology.

Environmental condition

- An ultrasonic anemometer shall be installed to measure the wind speed and direction.
- A rain gauge shall be installed to measure the rainfall.
- A seismometer shall be installed to measure the earthquake acceleration.
- A thermometer shall be installed to check the air temperature.

The SHM system of the Vam Cong bridge shall be established for the construction stage and service stage, respectively. In the construction stage, measurement data shall be transferred from DAQ equipment to the SHM system servers of the field office by using wireless communication technology. The SHM system servers shall be located in the maintenance office in the service stage, and web-based monitoring software shall be installed by using an internet network (Fig. 8) [4].

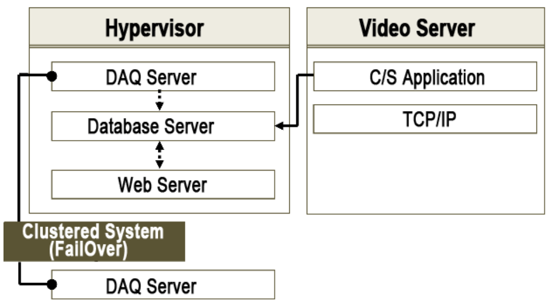

Fig. 8 Hardware architecture of operation system

The SHM system server is composed of a DAQ server, video server, and backup server. The clustered system shall operate the DAQ server with the redundant server (backup server) to keep the system stable in case of unexpected problems such as communication error and hardware trouble (Fig. 9).

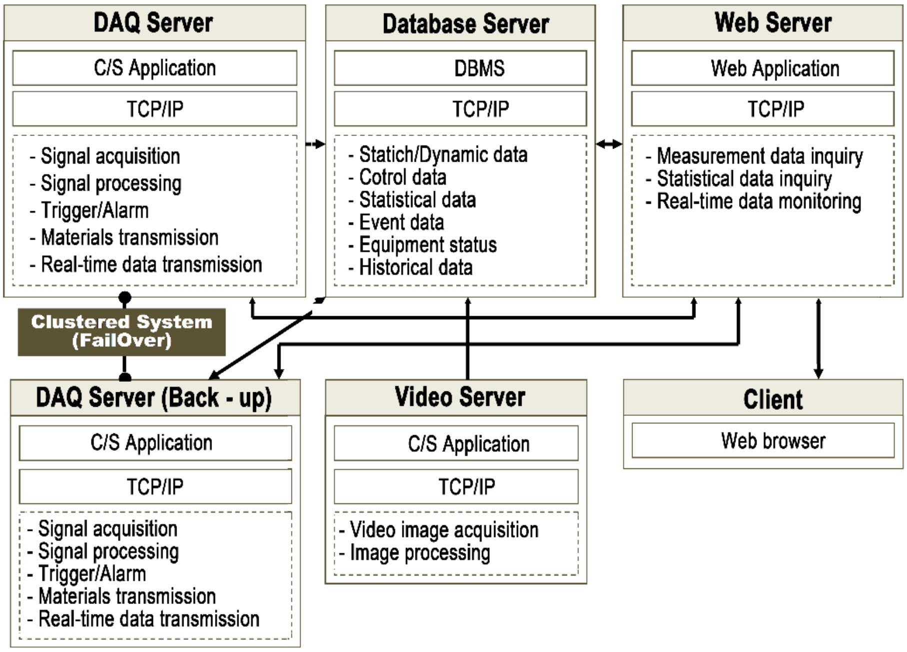

Fig. 9 Operation system architecture of SHMS

4.1.2. Measurement items of the constructions stage

Measurement items and locations in the SHM system for the Vam Cong bridge at the construction stage are tabulated and shown in Table 2 below. The location of the measuring sensors during the construction of the bridge is presented in Fig. 10 and Fig.11 below [4].

Table 2. Measurement items for the construction stage

Symbol	Sensor	Quantity	Location	Measurement items
	Anemometer	2	Top of PY2 Deck on PY2 table	wind velocity/directions
	Cable sensor	2	Longest cables	cable force
	Cable force	1	Portable device	cable force
	Strain meter	4	2-Adjacent to pylon table of PY1 2-Adjacent to pylon table of PY2	Stress of pylon
	Intelligent Camera	4	2-Top cross-beam of PY1 2-Top cross-beam of PY2	Bridge condition
	Water lever camera	1	Adjacent to PY2	Water level
	Thermometer	6	Top of PY2 Deck on PY2 table 2-PY1 inside 2-PY2 inside	Air Temp. Temp. in the pylon
	2-axis accelerometer	2	Top of PY1 Top of PY2	Vibration of pylon

4.1.3. Constitution of the devices and equipment of the Vam Cong SHM system

Each sensor shall be connected to a data logger with cable, and the data logger shall be installed inside the pylon. During the construction stage, a data logger is connected to wireless communication equipment, and measurement data is transferred to the field office. During the service stage, the data loggers located in each pylon are connected each other with optical cable and the SHM system servers with appropriate data processing software is installed inside the maintenance office. After the internet connection, SHMS is established for user to access the system. The diagram of SHM system is shown as Fig.12 follows.

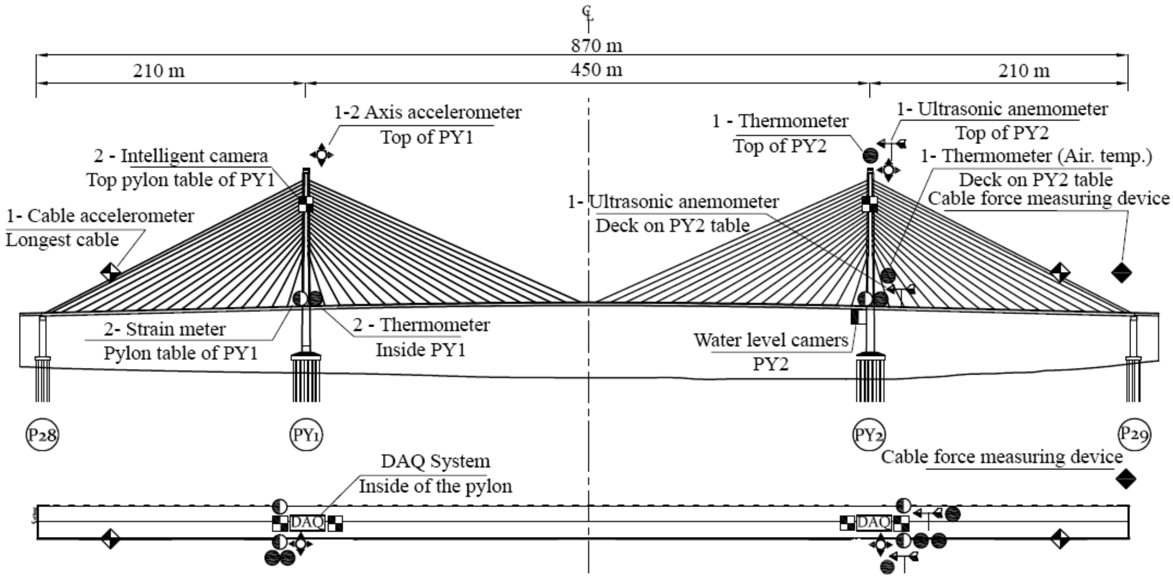

Fig. 10 Location of sensors in the construction stage at the side view of the bridge

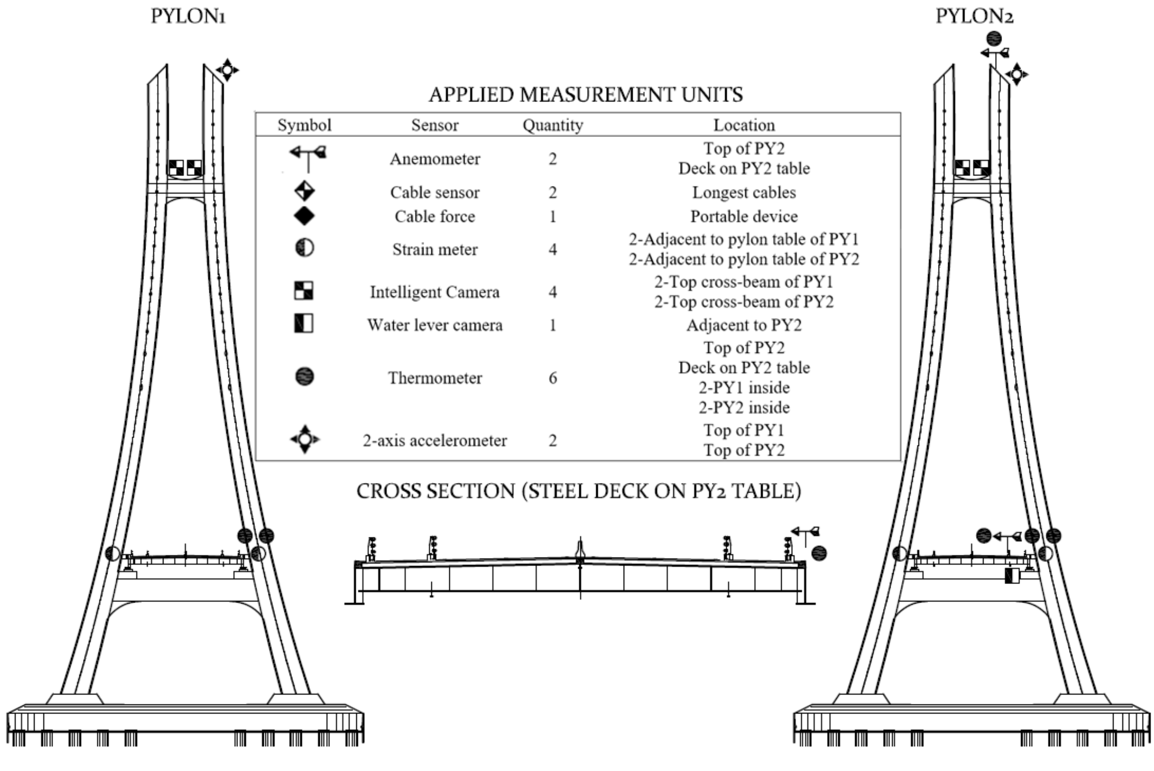

Fig. 11 Location of sensors in the construction stage at the pylon and cross-beam

Based on preliminary analysis of the SHM system designed for the Vam Cong bridge at the construction stage. There are few conclusions: The SHM system includes 22 sensors and measuring devices, focusing mainly on monitoring the construction site, weather conditions, the surrounding environment of the bridge area (anemometer, thermometer, IP camera, and water level camera). Only these devices operate during bridge construction. In addition, there are also accelerators and cable sensors to monitor the behavior of the pylons and stay cables during construction and adjust the tension in the longest cable. However, this system shows that it is elementary, only for monitoring and measuring, without analyzing the observed factors. Therefore, this system only achieves the simplest level - Level 1 (basic) [5, 6], as shown in Table 1 (Fig. 12).

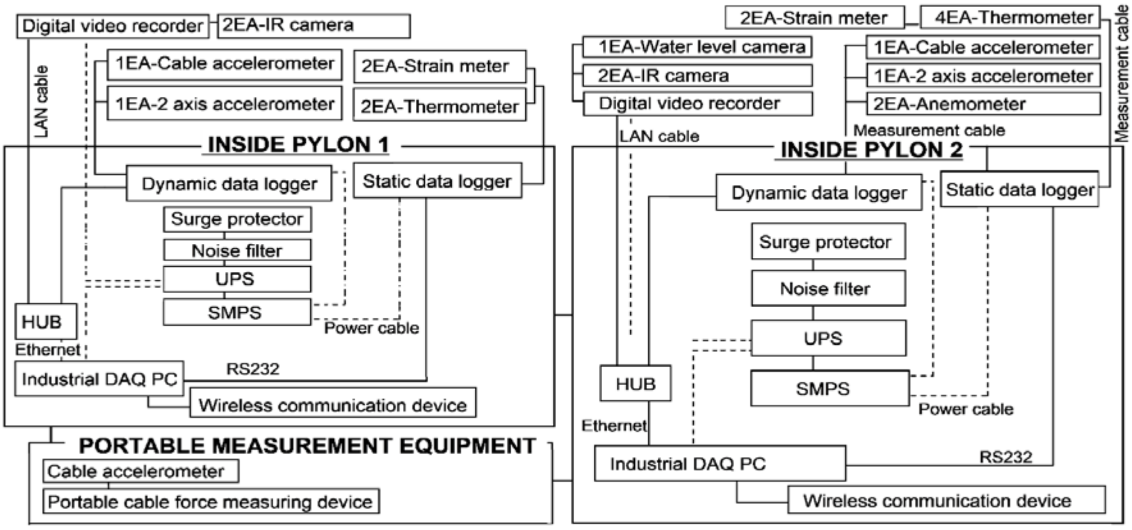

Fig. 12 Constitution of SHM system in the construction stage

4.1.4. Measurement frequency

The measurement under construction shall be based on the temporarily installed automated devices. Sensors and automated measurement equipment shall be installed in the appropriate stage considering the construction process. A detailed schedule of sensor installation for service stage maintenance shall be determined based on the discussion with the Engineer. Measurement for the maintenance process during the service stage begins after the completion of all the construction procedures. Measurement frequency shall be determined considering the objectives and types (static/dynamic) of measurement. Measurement frequency can be discussed and readjusted with the Engineer concerning the types of data and site conditions [4].

Table 3. Installation time and measurement frequency at construction stage [4]

Sensor	Location	Measurement	Installation time	Frequency
Anemometer	Pylon	Static/Dynamic	After pylon construction	10 min
Accelerometer	Deck	Dynamic/static	After deck construction	10 min
Cable force	Longest cables	Dynamic	After cable tensioning	-
Strain meter	Portable device	Static	Before cable tensioning	10 min
IP Camera	Pylon, Steel girder	-	After pylon construction	30 fr/s
Water lever camera	Pylon	-	After pylon construction	30 fr/s
Thermometer	Pylon Deck Dummy cable Steel girder	Static	After pylon construction After Deck construction After dummy cable set-up After construction completing	10 min
Accelerometer	Pylon	Static	After pylon construction	10 min

4.2. The Mistakes in Equipment and Devices Installation

The main installation requirement of the devices and the equipment is [6-8]:

- The devices and sensor must be installed correctly as a technical requirement
- General maintenance and inspection shall be carried out efficiently for the equipment.
- The joints connector shall be used for electrical connection between the equipment or the devices.
- Plug-in units shall be applied to the housing package of the devices for the efficient workability of maintenance.

During the field survey, after installing the monitoring equipment during the construction stage, according to Table 3, few monitoring devices were deinstalled, includes:

- a dual-axis accelerometer on the top of the pylon
- accelerometer at the bridge deck
- anemometer the top of the pylon

Thus, the remaining monitoring devices are only construction surveillance cameras, water level, temperature, and strain sensors at the tower's base (Fig. 15 and Fig. 16). The contractor explained this by dismantling the equipment mentioned above because it is expensive equipment, so it needs to be dismantled during the construction phase to ensure that the equipment is not damaged or exceeded. Therefore, these devices will be reassembled after the bridge construction items have been completed. This can be one of the main reasons leading to the failure to monitor the bridge's behavior during the construction stage, adjust the cable tension and lead to the CB6 horizontal girder being damage without any sign or warning [9].

Fig. 13 Installation and calibration of the 2-axis accelerometer at the top of the pylon.

A dual-axis accelerator on the top of the pylon should be placed on the stainless-steel plate to keep the correct level of the device. In fact, the device is mounted directly to the concrete surface of the pylon (Fig. 13). The strain sensors are the only devices left to monitor the behavior of the base inside the bridge pylons. These sensors are carefully installed and calibrated (Fig. 14).

Fig. 14 Installation and calibration one of four strainmeters (with temperature sensor) inside the pylon

Fig. 15 The main screen of the IP Camera shown the approach bridge

Fig. 16 Installation of the intelligent IP Camera after pylon construction

As noted above, the anemometer and bridge deck accelerators were deinstalled after mounting in the right place (Fig. 17 and Fig. 18)

Fig. 17 Installation anemometer to monitor environment condition at the top of the pylon and 2-axis accelerometer at the bridge deck.

The technical boxes (DAQ and Video Server) of the monitoring system are installed quite sloppily and indiscriminately during the construction stage. The equipment is plugged in from an ordinary electrical socket, not through the circuit breakers, to avoid overloading, which may lead to damaged monitoring devices (Fig. 19)

Fig. 18 DAQ Server and Video Server of the SHM system after installation at the construction stage

The Vam Cong bridge SHM system design at the construction stage should be a cable sensor (dual-axis accelerator) near the anchor to monitor the amplitude of the longest cable. Still, there was nothing like that at the time of the survey (Fig. 19).

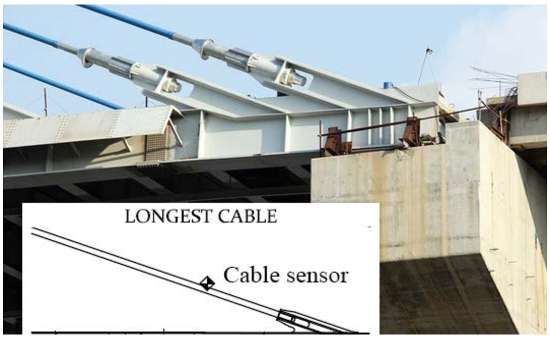

Fig. 19 The location of the cable sensor of the longest cable to monitoring cable amplitude.

5. CONCLUSION

Cables support a cable-stayed bridge, and the negative reaction occurs by cables at the anchor pier. It is a serious matter for the CB6 cross beam to be ripped with a 2m long and 4cm wide crack.

The following reasons can cause this damage:

- Inappropriate structural design;
- Steel material is too brittle;
- The design of the combination of loads is not suitable for the real condition;
- Process of the manufacturing beams not following regulations;
- Transporting and assembling beams;
- Deformation after construction of the bridge deck

However, the above factors can be partially eliminated or detected early if the bridge monitoring system during construction is installed and operated correctly according to design requirements. Use an acoustic emission evaluation for steel structures can detect early damage processes [9, 10]. The monitoring system based on the measurement of acoustic emission signals accompanying destructive processes cover the entire volume of the element under test or its selected part and allows locating and identifying active, destructive processes and their dynamics in real-time [11, 12].

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