Structural Health Monitoring System of the Thuan Phuoc Suspension Bridge in Viet Nam

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Abstract. In Viet Nam, one of the most important matters about The Large Bridge Construction is longevity during the exploitation phase and structural resistance to wind storms. System of Structural Healthy Monitoring such as solution to the this problem. This article gives information about Structural Health Monitoring (SHM) system on Thuan Phuoc Suspension Bridge in Viet Nam. Some dangerous phenomena occur only under the combination of certain practical conditions such as the vibration of stay cables due to combined wind and rain in storms, earthquakes… Installation system include sensor, controller and software get data about vibration frequency, stress, strain and temperature values in structural components to monitor the behavior of structures during exploitation, analysis and evaluation is important from that. The monitoring system will provide a comprehensive assessment of the state of the structure, as well as possible early detection of abnormalities to take appropriate measures in time, avoiding unfortunate consequences.

Keywords: Structural Longevity; Thuan Phuoc Suspension Bridge; Structural Health Monitoring System(SHMS); Sensor; Controller; Website Monitor; Fast Fourier Transform (FFT).

1 Introduction

Nowaday, for bridges construction, monitoring with high reliability is extremely important. In addition to the main request of control of the construction process as well as the detection of damages or deterioration in the exploitation process, SHM system also provides quantitative data for evaluation, collected data can be used for research, improvement of construction methods, design work. During the exploitation phase, monitoring data is used to assess the extent of damage, deterioration, structural capacity, incident or abnormal behavior. To build the plans on maintenance and repair, to ensure normal operation and effective exploitation of the works*[1]*.

Currently, monitoring activities for large span bridge have been established in many countries around the world and in the region. In Vietnam, the monitoring system is designed and installed in many large bridges such as Nhat Tan Bridge, Nguyen Van Troi - Tran Thi Ly Bridge, Can Tho Bridge, Cao Lanh Bridge, Nhat Le Bridge, - Crossroads of Nga Ba Hue... Several examples related to the recently constructed bridge observation system will be introduced as a basis for comparing and constructing a suitable monitoring system for the Thuan Phuoc suspension bridge*[1]*.

Thuan Phuoc bridge is suspension bridge, it has a large span and a multiple indeterminate structure, large distortion, the width of the bridge is 18 meters with steel girder, bridge tower is 80 meters high from the top of the tower base. Monitoring of vibration frequencies, stresses, deformations, and temperatures in structural components to monitor the behavior of structures during exploitation is very important*[1]*.

Yearly, the assessment of bridge health can be done through periodic assessment. However, this requires the labour mobilization is large, time-consuming and sometimes even demanding stoppages of the means on the bridge to carry out loading and measuring, not to mention the dangerous nature of this work for human participation. In addition, periodic inspections can record transient phenomena at the time of assessment, can not cover the entire operation of the under activities of bridge in various conditions. On the other hand, some dangerous phenomena occur only under certain combinations of practical conditions, such as the vibration of stay cables due to combined wind and rain, which can not be generated by people to serve the test. Therefore, the build of an automatic monitoring system, at the same time monitor many parameters and operate continuously over time can collect the important data. As a result, the monitoring and evaluation of bridge performance as well as can soon notice abnormalities in the structure to take appropriate measures in time, avoiding unfortunate consequences*[1]*.

Table 1. Testing result of 2015*[1]* and results of the design drawings for construction of Thuan Phuoc Bridge *[2]*

Results	Testing result of 2015	Design drawings for construction	Section
Frequency	0.267 (Hz) 0.597 (Hz)	0.258 (Hz) 0.658 - 0.933 (Hz)	¼; ½ Main girder ¼; ½ Main cable
Tension of live load	52.513 (tons)	37.05 (tons)	Suspender cable
Deflection of live load	692 (mm)	1500 (mm)	½ Steel girder
Stress of live load	35 (Mpa); -28 (Mpa)	50 (Mpa); -50(Mpa)	½ Steel girder

2 Methods of Thuan Phuoc Bridge Structural Health Monitoring System

2.1 Calculation Model

Using finite element method (FEM) to model the bridge structure, to compare update analysis with monitoring results to determine the model that is most compatible with the current monitoring results as the basis determines the initial state of the bridge. The analysis of the alarm threshold values of the sensors is also analyzed on this model.

MIDAS-civil and SAP2000 software used to analyze the model. The results of the analysis are compared with the results of the design calculations, the results of the latest load test (2015) and the results of observations at the present time (2018). The results of model analysis and determination of warning threshold values are as follows:

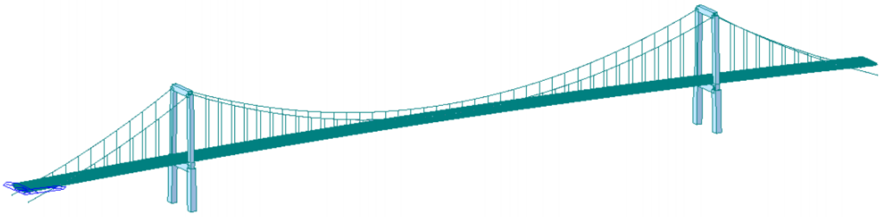


Fig. 1. Analysis model on software

The X axis is the bridge axis, the Y axis is the bridge and the Z axis is the vertical axis.

Tension in main cable, initial state as follows:

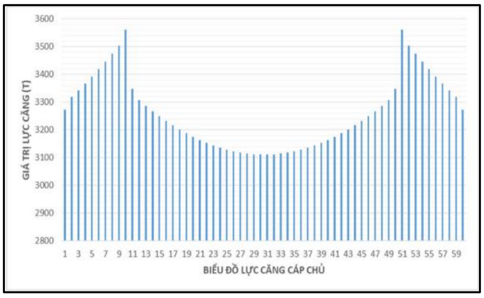


Fig. 2. Tension in main cable, initial state
Midas 2017

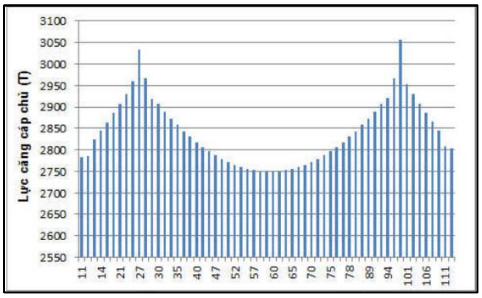


Fig. 3. Tension in main cable, initial state
Sap 2000

Tension in suspender cable, initial state as follows:

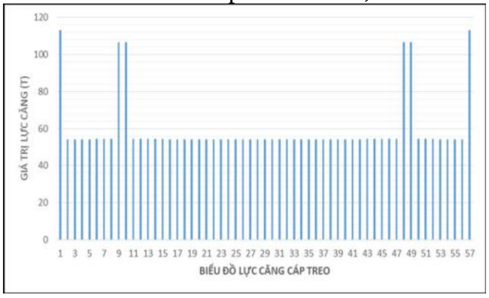


Fig. 4. Tension in suspender cable, initial state
Midas 2017

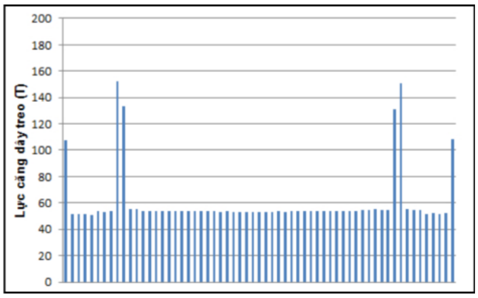
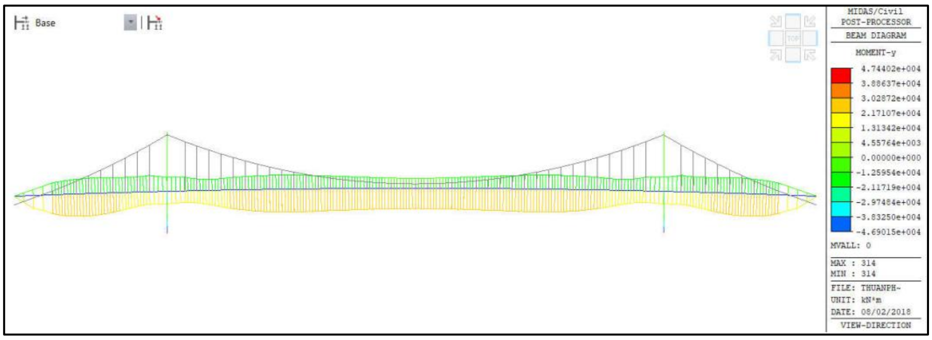


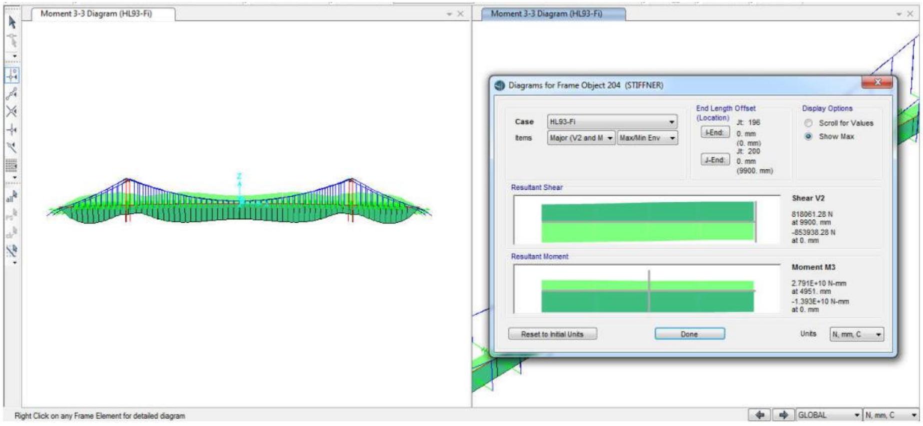
Fig. 5. Tension in suspender cable, initial state
Sap 2000

Moment of live load 0.65HL93 as follows:



```
MIDAS/Civil
POST-PROCESSOR
BEAM DIAGRAM
MOMENT-y
 4.74402e+004
 3.88637e+004
 3.02872e+004
 2.17107e+004
 1.31342e+004
 4.55764e+003
 0.00000e+000
-1.25954e+004
-2.11719e+004
-2.97484e+004
-3.83250e+004
-4.69015e+004
MVALL: 0
MAX : 314
MIN : 314
FILE: THUANPH~
UNIT: kN*m
DATE: 08/02/2018
VIEW-DIRECTION
```

Fig. 6. Moment of live load 0.65HL93 on Midas 2017



Case: HL93-Fi

Items: Major (V2 and M | Max/Min Env

End Length Offset (Location)
I-End: Jt: 196
0. mm
(0. mm)
J-End: Jt: 200
0. mm
(9900. mm)

Display Options
○ Scroll for Values
● Show Max

Resultant Shear

Shear V2
818061.28 N
at 9900. mm
-853938.28 N
at 0. mm

Resultant Moment

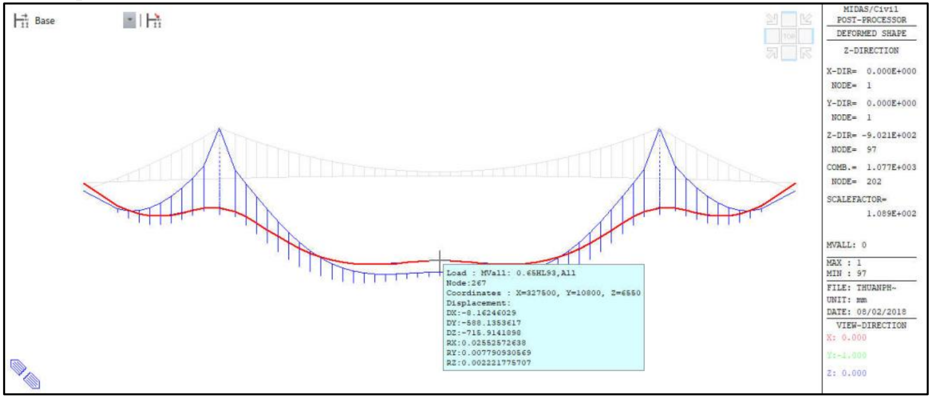
Moment M3
2.791E+10 N-mm
at 4951. mm
-1.393E+10 N-mm
at 0. mm

Units: N, mm, C

Right Click on any Frame Element for detailed diagram

Fig. 7. Moment of live load 0.65HL93 on Sap 2000

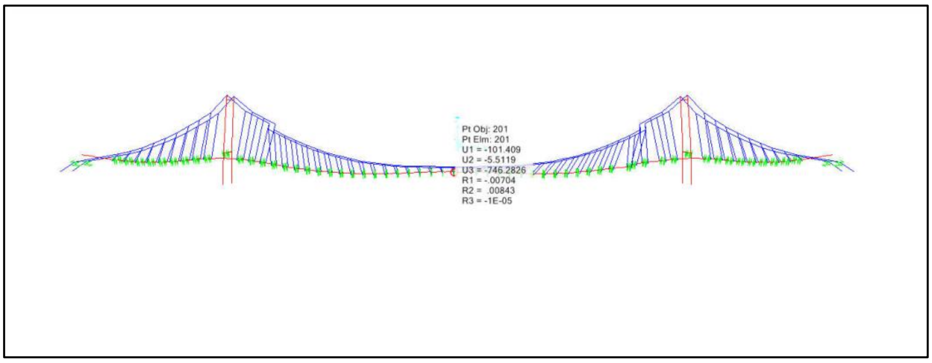
Displacement of live load 0.65HL93 as follows:



```
Load : MVall: 0.65HL93,All
Node:267
Coordinates : X=327500, Y=10800, Z=6550
Displacement:
DX:-8.16246029
DY:-588.1353617
DZ:-715.9141898
RX:0.02552572638
RY:0.007790930569
RZ:0.002221775707
```

```
MIDAS/Civil
POST-PROCESSOR
DEFORMED SHAPE
Z-DIRECTION
X-DIR=  0.000E+000
 NODE=  1
Y-DIR=  0.000E+000
 NODE=  1
Z-DIR= -9.021E+002
 NODE=  97
COMB.=  1.077E+003
 NODE=  202
SCALEFACTOR=
        1.089E+002
MVALL: 0
MAX : 1
MIN : 97
FILE: THUANPH~
UNIT: mm
DATE: 08/02/2018
VIEW-DIRECTION
X: 0.000
Y:-1.000
Z: 0.000
```

Fig. 8. Displacement of live load 0.65HL93 on Midas 2017



```
Pt Obj: 201
Pt Elm: 201
U1 = -101.409
U2 = -5.5119
U3 = -746.2826
R1 = -.00704
R2 =  .00843
R3 = -1E-05
```

Fig. 9. Displacement of live load 0.65HL93 on Sap 2000

Stress due to temperature TU in stiffening steel girder:

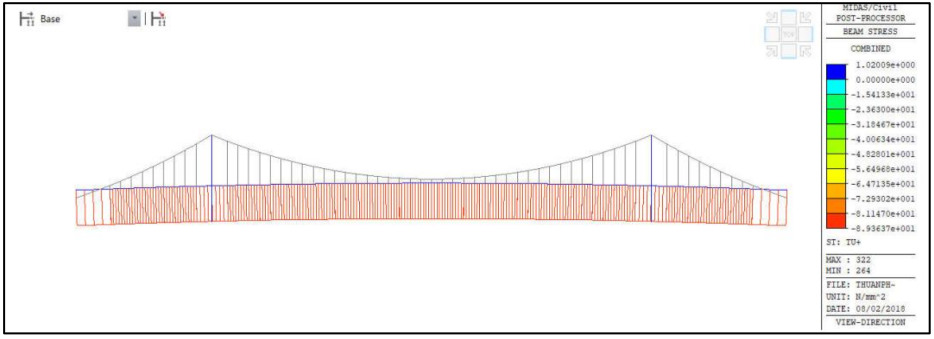


Fig. 10. Stress due to temperature TU+ = 38˚C on Midas 2017

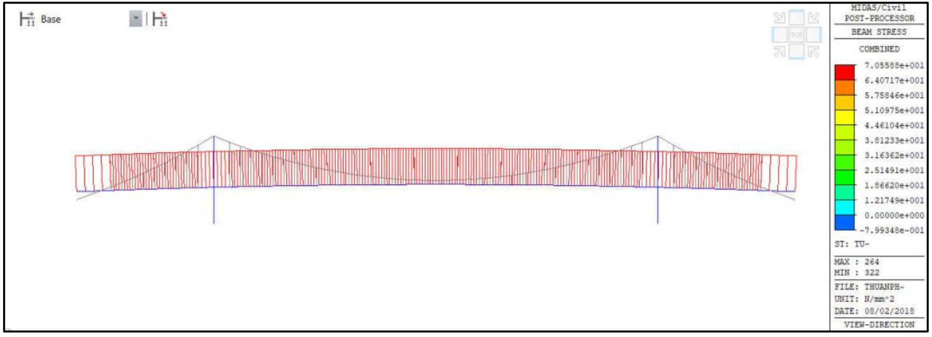
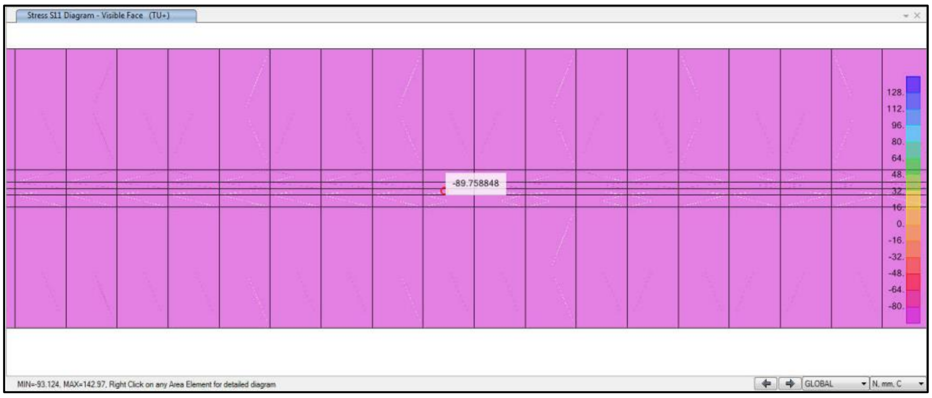
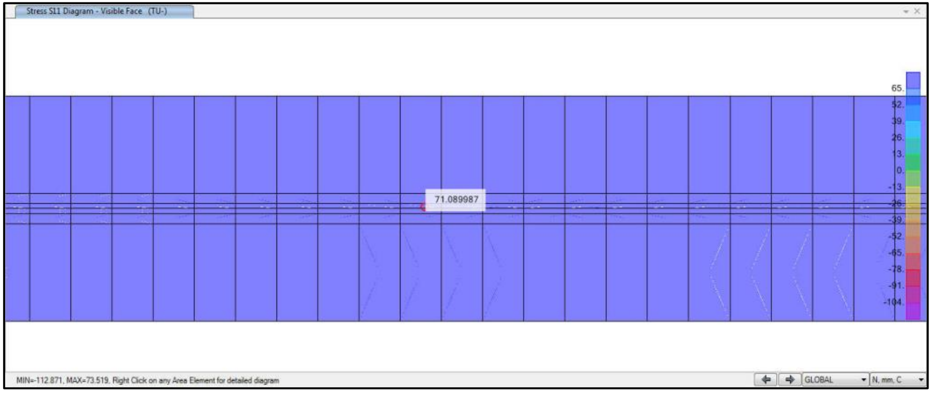


Fig. 11. Stress due to temperature TU+ = -30˚C on Midas 2017



```
MIN=-93.124, MAX=142.97, Right Click on any Area Element for detailed diagram
```

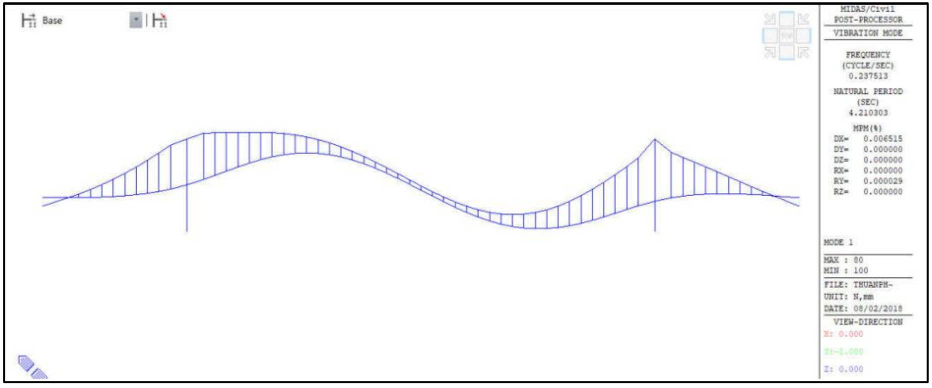
Fig. 12. Stress due to temperature TU+ = +38˚C on Sap 2000



```
MIN=-112.871, MAX=73.519, Right Click on any Area Element for detailed diagram
```

Fig. 13. Stress due to temperature TU+ = -30˚C on Sap 2000

Vibration of suspension

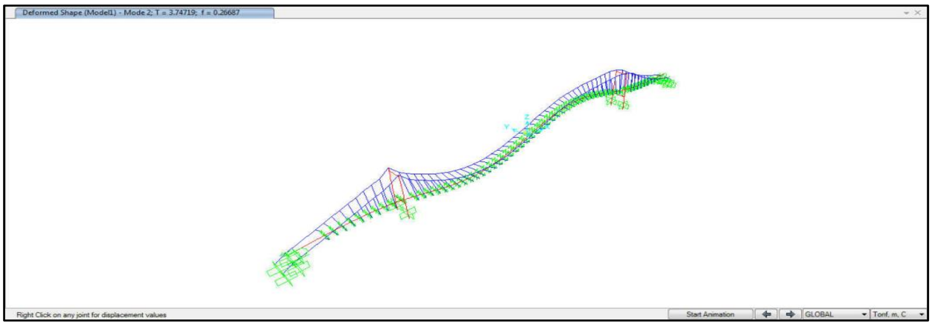


```
MIDAS/Civil
POST-PROCESSOR
VIBRATION MODE

FREQUENCY
(CYCLE/SEC)
0.237513
NATURAL PERIOD
(SEC)
4.210303
MPM(%)
DX=   0.006515
DY=   0.000000
DZ=   0.000000
RX=   0.000000
RY=   0.000029
RZ=   0.000000

MODE 1
MAX : 80
MIN : 100
FILE: THUANPH-
UNIT: N,mm
DATE: 08/02/2018
VIEW-DIRECTION
X: 0.000
Y:-1.000
Z: 0.000
```

Fig. 14. Vibration on Model 1 f=0.238Hz – Midas 2017



Deformed Shape (Model1) - Mode 2; T = 3.74719; f = 0.26687

Right Click on any joint for displacement values

Fig. 15. Vibration on Model 2 f=0.267Hz – Sap 2000

Table 2. General results from the calculation model

Model / **Location**	**Analysis model CsiBridgeV20 (Sap2000V14)**		**Analysis model Midas2017**	
	Max	***Min***	***Max***	***Min***
Stress on top fibers above of L/2 due to live load + temperature (Mpa)	46.65	-138.56	48.40	-123.00
Stress on bottom fibers below of L/2 due to live load + temperature (Mpa)	131.95	-48.55	120.20	-46.90
Stress on top fibers above of L/4 due to live load + temperature (Mpa)	39.80	-144.70	43.90	-127.20
Stress on bottom fibers below of L/4 due to live load + temperature (Mpa)	140.17	-39.73	128.00	-41.40
Vibration Frequency (Hz)	0.2668		0.2375	
Tilts L/2 horizontal axis (degree)	0.928	-0.928	1.463	-1.463
Tilts L/2 longitudinal axis (degree)	-	-	0.446	-0.446

Table 3. Comparison of calculation results and accreditation results for 2015*[1][2]*

Model / **Location**	**Analysis model CsiBridge V20 (Sap2000 V14)**	**Analysis model Midas2017**	**Analysis model RM (Accredita-tion 2015)**	**Design data (China)**
Moment of L/2 due to live load 0.65HL93 (kN.m)	27910	24238	21000	-
Moment of L/4 due to live load 0.65HL93 (kN.m)	32710	27335	25918	-
Displacement of L/2 due to live load 0.65HL93 (mm)	746.3	715.9	630.0	-
Displacement of L/2 due to live load 0.65HL93 (mm)	761.9	743.3	704.9	-
Tension of main cable Maximum (T)	3050.0	3492.0	3537.6	-
Tension of suspender cable Maximum (T)	150.0	113.05	113.51	-
Vibration Frequency (Hz)	0.2668	0.2375	0.2591	0.2456

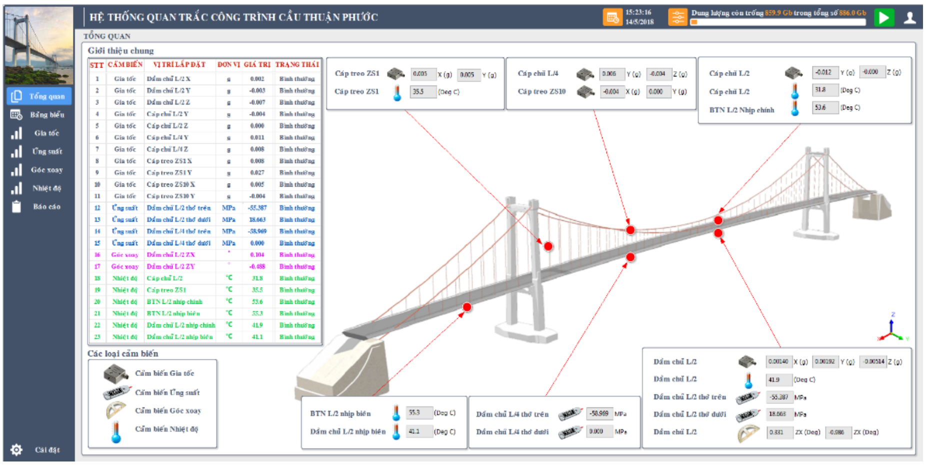
After comparing the results from the computational model, the consultant chooses the model with Midas Civil to calculate the warning threshold. In addition, due to the calculation model, factors such as structural changes during the construction process are not taken into account; the reduction of the material intensity after 10 years of use, so the consultant recommends the warning value included in the software by 75% of the value indicated in the table above, specifically:

Table 4. Warning threshold results

Model	Analysis model Midas2017	
Location	***Max***	***Min***
Stress on top fibers above of L/2 due to live load + temperature (Mpa)	36.30	-92.25
Stress on bottom fibers below of L/2 due to live load + temperature (Mpa)	90.15	-35.18
Stress on top fibers above of L/4 due to live load + temperature (Mpa)	32.93	-95.40
Stress on bottom fibers below of L/4 due to live load + temperature (Mpa)	96.00	-31.05
Tilts L/2 horizontal axis (degree)	1.10	
Tilts L/2 longitudinal axis (degree)	0.335	

2.2 Method of arrangement of monitoring system

The monitoring system is arranged in a clustered model, each cluster has a datalogger that connects to the surrounding sensors. The nodes are connected together by a network cable or fiber optic cable. The last node connected to the server is located one kilometer away from the optical node. Interface monitoring program is designed on the programming language of labview as shown below.



HỆ THỐNG QUAN TRẮC CÔNG TRÌNH CẦU THUẬN PHƯỚC

15:23:16
14/5/2018

Dung lượng còn trống 859.9 Gb trong tổng số 886.0 Gb

TỔNG QUAN

Giới thiệu chung

STT	CẢM BIẾN	VỊ TRÍ LẮP ĐẶT	ĐƠN VỊ	GIÁ TRỊ	TRẠNG THÁI
1	Gia tốc	Dầm chủ L/2 X	g	0.002	Bình thường
2	Gia tốc	Dầm chủ L/2 Y	g	-0.003	Bình thường
3	Gia tốc	Dầm chủ L/2 Z	g	-0.007	Bình thường
4	Gia tốc	Cáp chủ L/2 Y	g	-0.004	Bình thường
5	Gia tốc	Cáp chủ L/2 Z	g	0.000	Bình thường
6	Gia tốc	Cáp chủ L/4 Y	g	0.011	Bình thường
7	Gia tốc	Cáp chủ L/4 Z	g	0.008	Bình thường
8	Gia tốc	Cáp treo ZS1 X	g	0.008	Bình thường
9	Gia tốc	Cáp treo ZS1 Y	g	0.027	Bình thường
10	Gia tốc	Cáp treo ZS10 X	g	0.005	Bình thường
11	Gia tốc	Cáp treo ZS10 Y	g	-0.004	Bình thường
12	Ứng suất	Dầm chủ L/2 thớ trên	MPa	-55.387	Bình thường
13	Ứng suất	Dầm chủ L/2 thớ dưới	MPa	18.663	Bình thường
14	Ứng suất	Dầm chủ L/4 thớ trên	MPa	-58.969	Bình thường
15	Ứng suất	Dầm chủ L/4 thớ dưới	MPa	0.000	Bình thường
16	Góc xoay	Dầm chủ L/2 ZX	°	0.104	Bình thường
17	Góc xoay	Dầm chủ L/2 ZY	°	-0.488	Bình thường
18	Nhiệt độ	Cáp chủ L/2	°C	31.8	Bình thường
19	Nhiệt độ	Cáp treo ZS1	°C	35.5	Bình thường
20	Nhiệt độ	BTN L/2 nhịp chính	°C	53.6	Bình thường
21	Nhiệt độ	BTN L/2 nhịp biên	°C	55.3	Bình thường
22	Nhiệt độ	Dầm chủ L/2 nhịp chính	°C	41.9	Bình thường
23	Nhiệt độ	Dầm chủ L/2 nhịp biên	°C	41.1	Bình thường

Các loại cảm biến
Cảm biến Gia tốc
Cảm biến Ứng suất
Cảm biến Góc xoay
Cảm biến Nhiệt độ

Cáp treo ZS1 0.005 X (g) 0.005 Y (g)
Cáp treo ZS1 35.5 (Deg C)

Cáp chủ L/4 0.006 Y (g) -0.004 Z (g)
Cáp treo ZS10 -0.004 X (g) 0.000 Y (g)

Cáp chủ L/2 -0.012 Y (g) -0.000 Z (g)
Cáp chủ L/2 31.8 (Deg C)
BTN L/2 Nhịp chính 53.6 (Deg C)

BTN L/2 nhịp biên 55.3 (Deg C)
Dầm chủ L/2 nhịp biên 41.1 (Deg C)

Dầm chủ L/4 thớ trên -58.969 MPa
Dầm chủ L/4 thớ dưới 0.000 MPa

Dầm chủ L/2 0.00140 X (g) 0.00192 Y (g) -0.00514 Z (g)
Dầm chủ L/2 41.9 (Deg C)
Dầm chủ L/2 thớ trên -55.387 MPa
Dầm chủ L/2 thớ dưới 18.663 MPa
Dầm chủ L/2 0.331 ZX (Deg) -0.986 ZX (Deg)

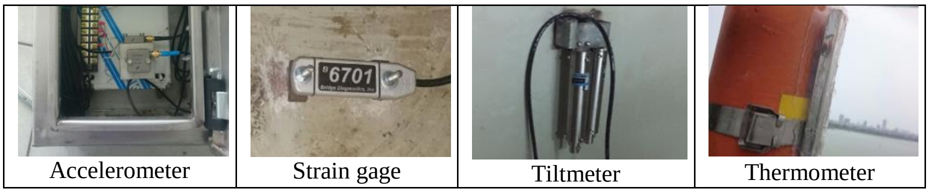
Fig. 16. General Installation location of the sensor

2.3 Data Acquisition Components

The system include three controller get data from sensor, sent to host computer at control room. In there, the collection and analysis software will display operation of sensor and calculated important value so that expert could real-time evaluate any time of the day.

Table 5. The number of sensor installed on the Thuan Phuoc SHM system (stage 1)

No.	Sensor type	Quantity
1	Accelerometer	11
2	Strain gage	4
3	Tiltmeter	2
4	Thermometer	6



Accelerometer Strain gage Tiltmeter Thermometer

Fig. 17. Sensors installed in the SHM system at the Thuan Phuoc Suspension Bridge

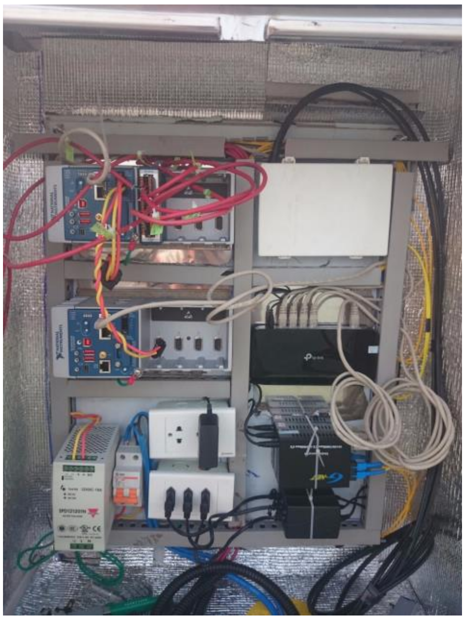


Fig. 18. The nodes of controllers are connected together by a network cable or fiber optic cable

4. Some results of initial monitoring

Data from thermometer, strain gauge, tiltmeters, and acceleration sensors are displayed on the monitoring interface and stored in disk in real time. A program designed specifically for data analysis and preparation of monitoring reports by week, month as follows:

Fig. 19. Panel of accelerometers sensor system

Fig. 20. Panel of strain gauges sensor system

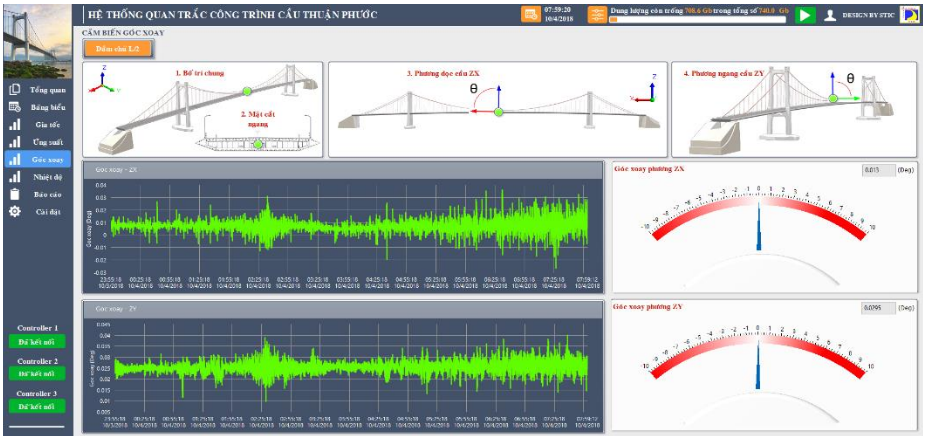


Fig. 21. Panel of tiltmeters sensor system

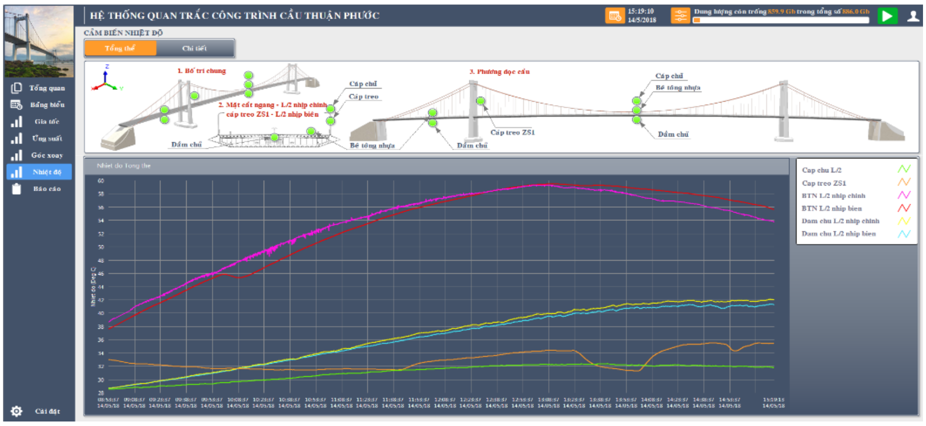
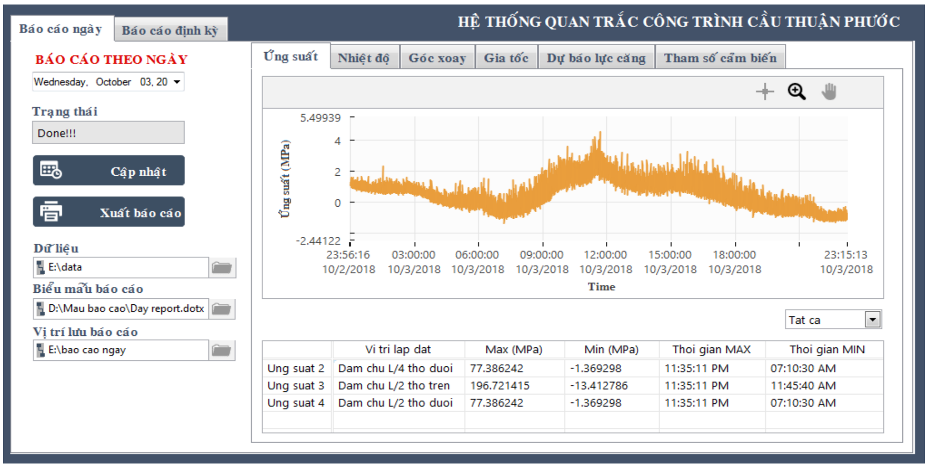


Fig. 22. Panel of thermometer sensor system



BÁO CÁO THEO NGÀY

Wednesday, October 03, 20

Trạng thái: Done!!!

Cập nhật

Xuất báo cáo

Dữ liệu: E:\data

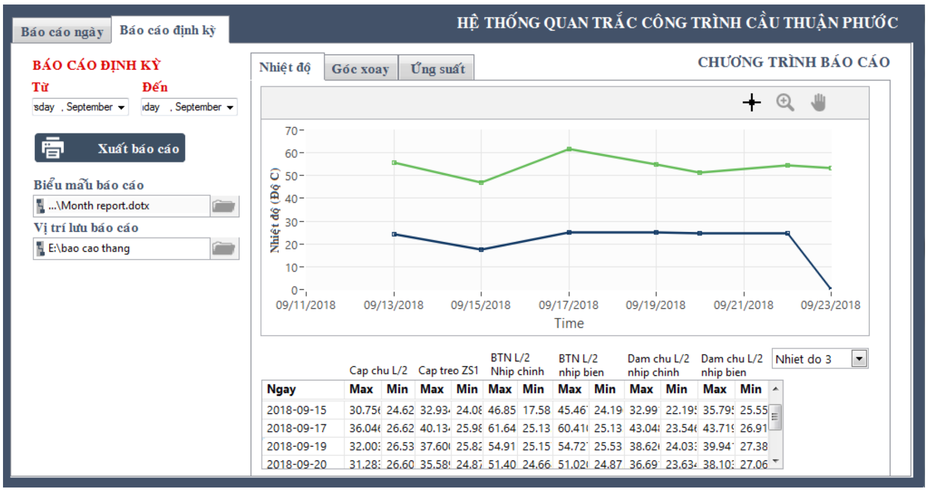
Biểu mẫu báo cáo: D:\Mau bao cao\Day report.dotx

Vị trí lưu báo cáo: E:\bao cao ngay

Tat ca

	Vi tri lap dat	Max (MPa)	Min (MPa)	Thoi gian MAX	Thoi gian MIN
Ung suat 2	Dam chu L/4 tho duoi	77.386242	-1.369298	11:35:11 PM	07:10:30 AM
Ung suat 3	Dam chu L/2 tho tren	196.721415	-13.412786	11:35:11 PM	11:45:40 AM
Ung suat 4	Dam chu L/2 tho duoi	77.386242	-1.369298	11:35:11 PM	07:10:30 AM

Fig. 23. The Program for data analysis and preparation of monitoring day reports



BÁO CÁO ĐỊNH KỲ

Từ: sday , September

Đến: iday , September

Xuất báo cáo

Biểu mẫu báo cáo: ...\Month report.dotx

Vị trí lưu báo cáo: E:\bao cao thang

Nhiet do 3

	Cap chu L/2		Cap treo ZS1		BTN L/2 Nhip chinh		BTN L/2 nhip bien		Dam chu L/2 nhip chinh		Dam chu L/2 nhip bien	
Ngay	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
2018-09-15	30.75	24.62	32.93	24.08	46.85	17.58	45.46	24.19	32.99	22.19	35.79	25.55
2018-09-17	36.04	26.62	40.13	25.98	61.64	25.13	60.41	25.13	43.04	23.54	43.71	26.91
2018-09-19	32.00	26.53	37.60	25.82	54.91	25.15	54.72	25.53	38.62	24.03	39.94	27.38
2018-09-20	31.28	26.60	35.58	24.87	51.40	24.66	51.02	24.87	36.69	23.63	38.10	27.06

Fig. 24. The Program for data analysis and preparation of monitoring month reports

For vibration frequency, data from accelerometer calculated through FFT calculation program, it is determined frequency peak and frequency value corresponding.

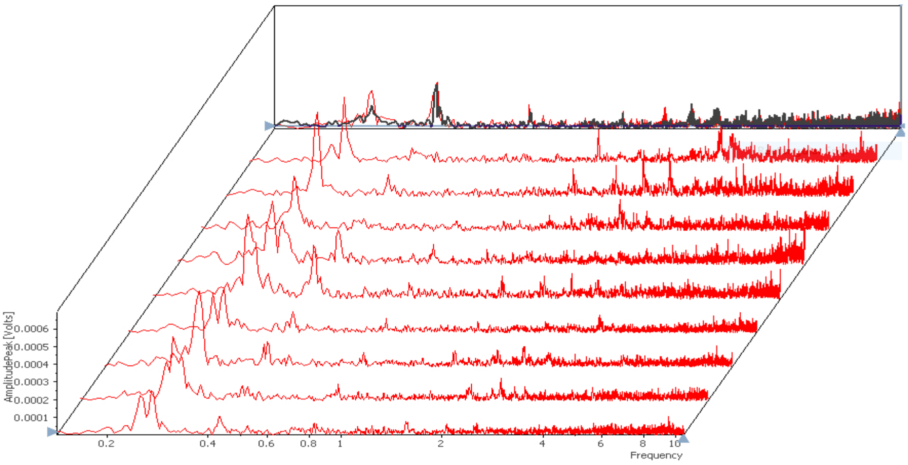


Fig. 25. Result of FFT f= 0.241(Hz) analyzed of accelerometer on ½ span main girder

The results obtained from the monitoring system are similar to the results obtained on the finite element model, the present value of the sensors in the safety value domain is calculated according to the data design.

3 Conclusions

The Thuan Phuoc Monitoring System provided by the group of authors has been designed and installed with relatively low cost compared to similar systems supplied by foreign companies. Graphical interface design in Labview environment allows for monitoring data in real time is quite convenient. The results of the analysis of the initial observation data show that the dynamic range of motion is relatively smaller than the change in stress spectrum which shown table above.

The results of individual vibration frequency analyzes from vibration acceleration sensors show that the specific vibration frequency of the real model is not much different from the FEM model used in the design to be exploited safely. However, it is necessary to consider additional environmental load factors such as wind, structural corrosion to assess the health of the bridge in the coming time is necessary.

With the system of monitoring, analysis and warning, Thuan Phuoc SHM system is considered as a step forward in monitoring technology in Vietnam with flexible operation and cost savings. Considered as modern and promising in the future.

References

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