EVALUATION AND MODEL IDENTIFICATION OF BRIDGE BASED ON HEALTH MONITORING SYSTEM: Case Study

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Contents

Introduction

Importance of efficient bridges management is more emphasized than ever in the present day, urging transportation officials seek innovative approaches to handle the aging highway bridge stock. Structural Health Monitoring (SHM) offers techniques for improving assessment methods significantly. Investigation of this study is on integrating SHM to assessment and evaluation health monitoring system and environmental effects on bridges. Many bridge failures caused by normal or abnormal loading. The process of implementing a damage identification strategy for civil infrastructures is referred to SHM.

Introduction

Bridge monitoring is the application of SHM and inspection techniques to bridge structures. The most common objectives for monitoring a bridge are to obtain quantitative data about the structural behavior in order to confirm design assumptions, and to evaluate the real current condition of the bridge. Such monitoring allows engineers to take informed decisions about their future and to plan maintenance or repair actions. Monitoring systems are used to increase the safety of the structure and provide early warning of an acceleration of the known degradations that are being monitored.

Introduction

Any structure that interacts directly with climatic agents is subject to non-stationary and spatially non-linear temperature fields that induce displacement and stresses. Changing atmospheric conditions creates differential temperatures through the cross-section of bridge superstructures. In the day time the deck part gains a large amount of heat from solar radiation while lower portions are still kept cooler because of a poor heat conductivity of concrete. The most severe condition occurs when a sunny, windless day follows a few days of cold weather. This is known as a positive thermal gradient. A negative thermal gradient occurs when a rainy, cold front interrupts a few days of hot weather. The negative thermal gradient is usually smaller and has less effect on structural design than the positive gradient

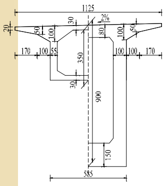
Study aims

The main objectives of this study are: monitoring and evaluation of Fu-Sui bridge and assessment the monitoring system design. The FEM design is used to compare the results of monitoring and simulation during monitoring period time. The de-noise and signal processing is used to improve the effect of loads and remove the vibration noised of sensors observations.

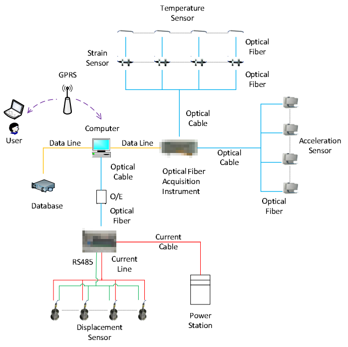
The models identification are used to identify model movement and damage of bridge to assessment the health state of bridge in future monitoring time, output only and input-output models is used in this study. In addition, the effect of temperature is main scope of this study because the hard environmental effects on the bridge study site.

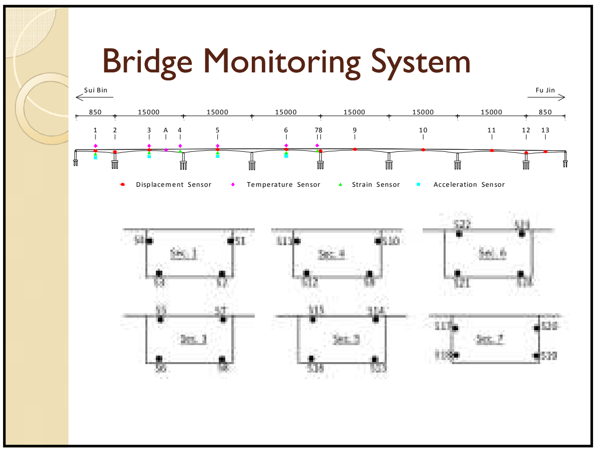
Fu-Sui Bridge

- Fu Sui Bridge, total 1170 m long, is a PSC continuous box-girder bridge located in Heilongjiang province, China (as shown in Fig.). It crosses the Song Hua River and connects two towns: Fu Jin and Sui Bin. The bridge is consisted of eight continuous spans of 85.00 m, 6*150 m, 85.00 m. The main girder, cast-in-place, post-tensioned segmental structure has a single-cell box cross section, with the height varying from 9 m (over pier section) to 3.5 m (mid-span section), including 11.25 m width of top slab, 5.85 m width of bottom slab and 2.7 m length of flange slab on each side.

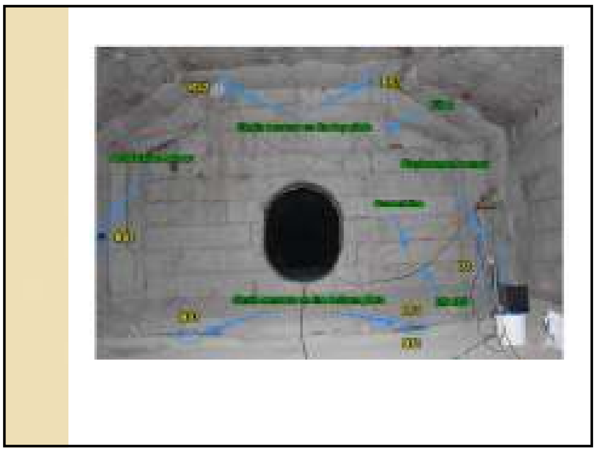


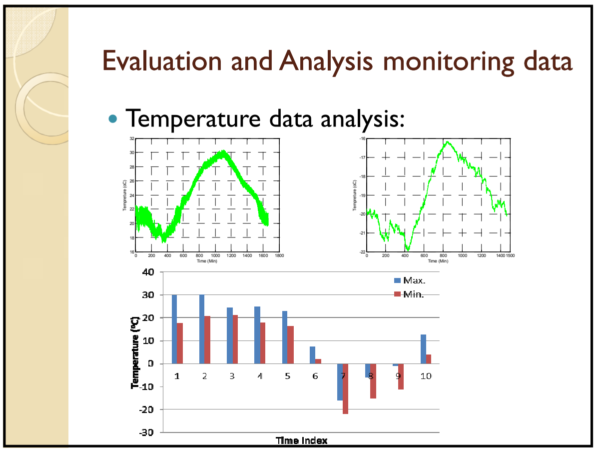
Bridge Monitoring System





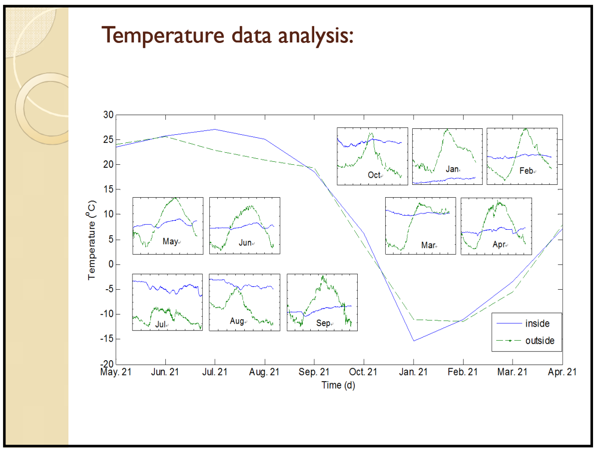
Bridge Monitoring System





Evaluation and Analysis monitoring data

- Temperature data analysis:



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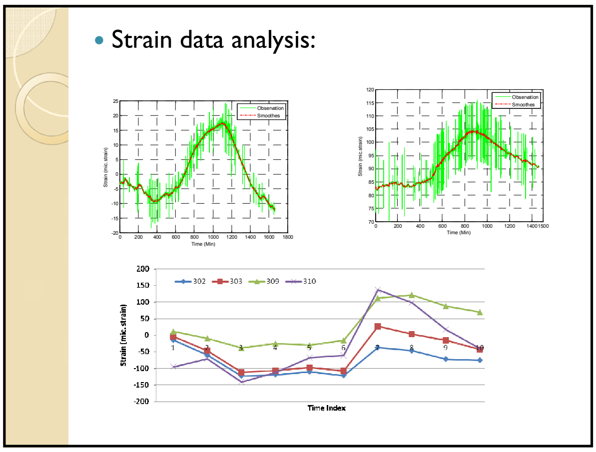
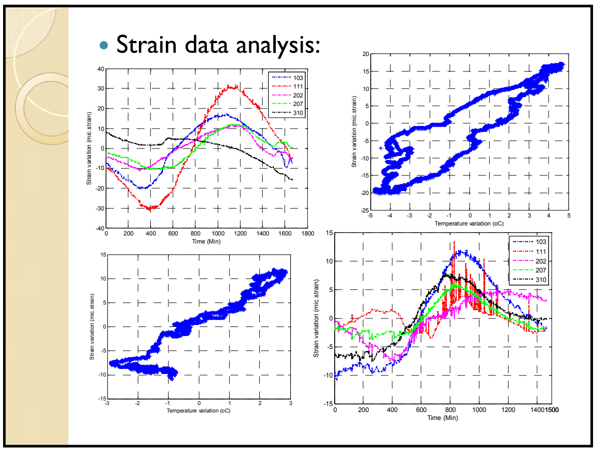


- Strain data analysis:



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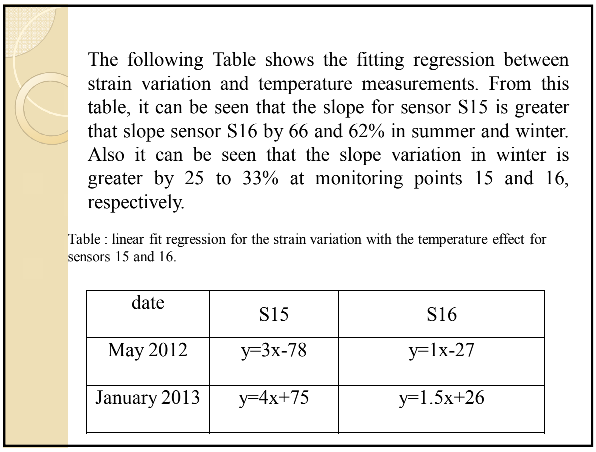
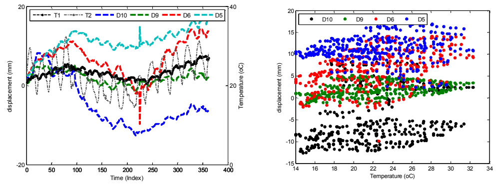


The following Table shows the fitting regression between strain variation and temperature measurements. From this table, it can be seen that the slope for sensor S15 is greater that slope sensor S16 by 66 and 62% in summer and winter. Also it can be seen that the slope variation in winter is greater by 25 to 33% at monitoring points 15 and 16, respectively.

Table : linear fit regression for the strain variation with the temperature effect for sensors 15 and 16.

date	S15	S16
May 2012	y=3x-78	y=1x-27
January 2013	y=4x+75	y=1.5x+26

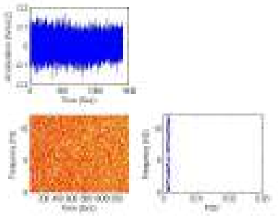
- Displacement monitoring data:



Monitoring points	Outside temperature relation	Inside temperature relation
D5	y=0.06x+9.8	y=1.3x-19
D6	y=0.46x-3.5	y=2.3x-48
D9	y=0.14x-1.2	y=0.45x-8.6
D10	y=0.41x-14	y=0.63x-19

- Acceleration monitoring data:

The Fast Fourier transformation (FFT) is used to calculate the frequency of acceleration data. The continuous wavelet transforms detect changes in the structure's natural frequencies by generating a time frequency (Short Time FT (STFT)) map of the response signal and it is more suitable for analyzing non-stationary signal records, such as those with discontinuities or signal sudden



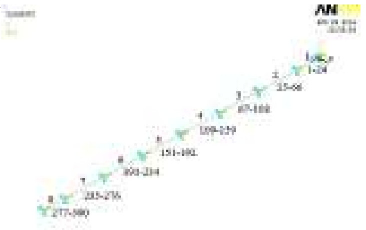
Acceleration monitoring data:

The following table presents the first mode detected based on the FFT method. From this table, it can be seen that the first frequency mode with monitoring date selection are very close. It means that the bridge's dynamic behavior is safe.

Date	May 2012	June 2012	January 2013	March 2013
First freq. mode	0.704	0.683	0.659	0.634

FE Model Analysis

The finite element model (FEM) of Fu-Sui Bridge was established by the ANSYS program to analyze the model frequencies and shapes. Beam element (BEAM4), six degrees of freedom on each code, was selected to simulate the real box girder



The first ten modal frequencies of this bridge ranged from 0.4Hz to 1.4Hz. Table shows the vibration properties.

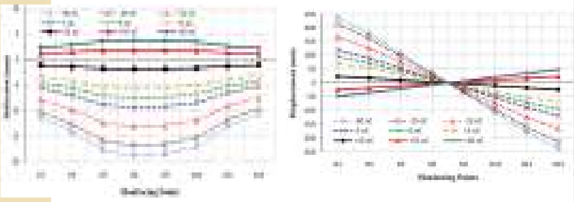
Model analysis features summary

Numerical frequency (Hz)	Nature of modes of vibration	
0.4233	Anti- symmetrical	First vertical bending
0.5536	Symmetrical	Second vertical bending
0.7245	Anti –symmetrical	Third vertical bending
0.7436	Anti –symmetrical	First lateral bending
0.8728	Symmetrical	Second lateral bending
0.9187	Symmetrical	Fourth vertical bending
1.0564	Anti –symmetrical	Third lateral bending
1.1299	Anti –symmetrical	Fifth vertical bending
1.2728	Symmetrical	Fourth lateral bending
1.3565	Symmetrical	Sixth vertical bending

The following Fig. shows the first two calculated mode shapes of vertical bending and lateral bending.

(b) 1st VB mode f=0.4233Hz (c) 2nd VB mode f=0.5536 Hz (d) 1st LB mode f=0.7436Hz (e) 2nd LB mode f=0.8728 Hz

The following Fig. shows the deflection and displacement for points D1,3,5,6,9,10,11 and 13 due to temperature effects. A reference temperature of 20 °C was adopted in compliance with the bridge design and the real closure temperature while the displacement and deflection of monitoring points was calculated based on FEM.



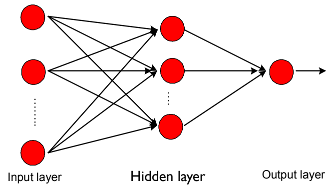
The following Table presents the maximum strain variation values at the upper and lower monitoring points with the temperature change.

FEM strain point monitoring with temperature effects (μ ε)

Temperature	Upper elements				Lower elements			
	1	3	5	6	1	3	5	6
-30	-0.676	9.045	13.467	16.067	3.867	20.467	33.556	39.111
-15	-0.473	6.333	9.422	11.244	2.711	14.333	23.555	27.333
0	-0.271	3.622	5.378	6.422	1.542	8.2	13.422	15.667
15	-0.067	0.904	1.346	1.607	0.387	2.047	3.356	3.911
30	0.135	-1.807	-2.689	-3.222	-0.771	-4.089	-6.711	-7.844

output-only Model Identification

This study used a neural network model of a dynamic system based on the Recursive algorithm AutoRegresive Moving average with eXogenous inputs (NNRARMX) to identify the thermal response of the upper and bottom bridge decks in summer and winter based on output from the thermal response only.



$$\hat{y}_i = F_i\left(\sum_{j=1}^{q} W_{ij} f_j\left(\sum_{l=1}^{m} w_{jl}\varphi_l + w_{j0}\right) + W_{i0}\right)$$

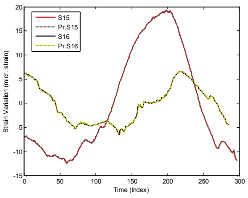
The neural network learning process is to apply corrective adjustments to the synaptic weight of the neuron function used in order to make the output come closer to the desired response in a step-by-step manner that satisfies the minimum loss function and the Akaike's Final Prediction Error (FPE).

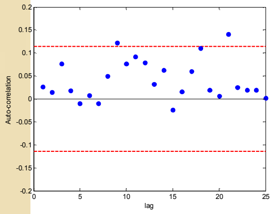
- Thermal response model identification

from the following Table, it can be concluded that the NNRARMX [3] and [20] models are suitable to predict the thermal response of the bridge. In addition, it is clearly seen that the models' outputs are in conformity with the observations strain. ACF and 95% confidence intervals of the models' residuals are also presented, It can be concluded that no loss of information was observed since the residuals of these models stayed within the confidence interval of the autocorrelation function.

Model	May 2012				January 2013			
	S15		S16		S15		S16	
	FPE	R^2	FPE	R^2	FPE	R^2	FPE	R^2
NNRARMX [3]	0.012	0.99	0.021	0.95	0.027	0.98	0.011	0.97
NNRARMX [20]	0.014	0.98	0.020	0.98	0.036	0.98	0.01	0.98

- Thermal response model identification



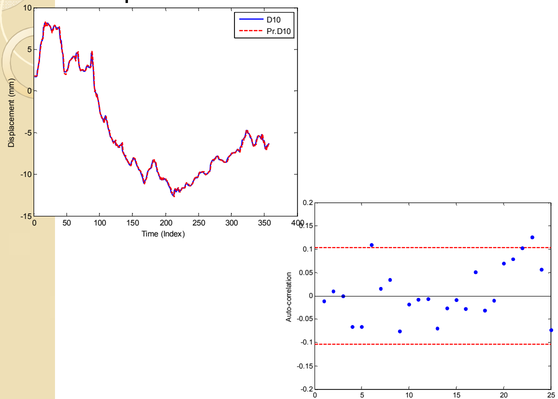


- Displacement model identification:

From this table it can be seen that the most suitable model that can be used is NNRARMX [5]. This means that the displacement of the bridge deck also has a non-linear behavior with monitoring time. And the Fig. shows the prediction of the output-only NNRARMX [5] model and next Fig. shows the ACF and 95% confidence of the residuals model. From these results, it can be concluded that no loss of information was observed since the residuals of this model stayed within the confidence interval of the autocorrelation function.

Model	FPE	R^2
NNRARMX [3]	0.035	0.97
NNRARMX [5]	0.023	0.98
NNRARMX [10]	0.024	0.98
NNRARMX [20]	0.024	0.97

- Displacement model identification:



Single Input-Single Output Identification Thermal Response Model of Bridge

In this part used single input-single output Nonlinear regression with least square solution and NonLinear AutoRegresive with eXogenous inputs (NLARX) with wavelet neural networks models to identify the thermal response of bridge to estimate the nonlinearity model parameters.

1. Nonlinear regression (NR) model

In this study consider a power nonlinear function fitted model:

$$y_i = a + b_1T_i + b_2T_i^2 + b_3T_i^3 + \cdots + b_kT_i^k + e_i \quad (i = 1,2, \dots \dots, n)$$

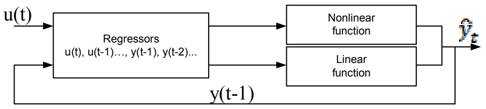
the unknown parameters (X^T=[a b_1 …..b_k]) can be estimated and tested for statistical significance using least square method.

$$X = (A^TWA)^{-1}A^TWy$$

A is the design matrix, *y* is the vector of the *n* observed output quantities, and *W* is the new weight matrix.

2. Nonlinear ARX Wavelet Network (WN) model

the NLARX model as shown in Fig is the extension of the ARX model and a model of order *P* is given by Eq:



$$\hat{y}_t = f\left(\sum_{i=1}^{p} a_{t-i}\, y_{t-i}\right) + e_t$$

y_{t-i} are previous system states (y) and input (u) observations

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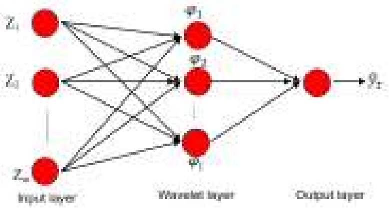
the Multilayer Perceptron Network (MPN) considered here ; furthermore confined to those having only one hidden or wavelet layer and linear activation functions (f,F):



$$h(j) = \varphi_j\left[\frac{\sum_{i=1}^{m} w_{ij} z_i - b_j}{a_j}\right], \quad j = 1,2,\ldots p$$

$$\hat{y}_t = \sum_{i=1}^{p} W_{it} h(i), \quad t = 1,2,\ldots,k$$

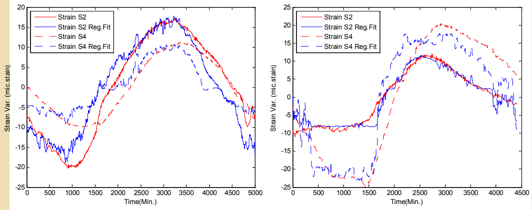
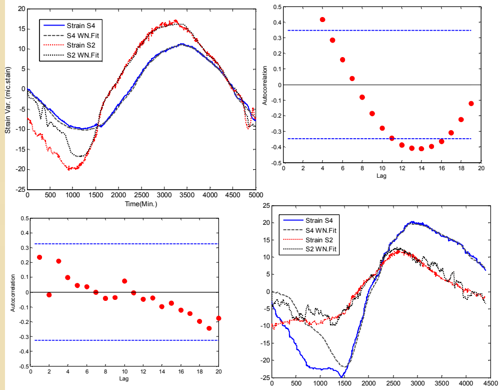


Table 1. NR model for S2 strain monitoring summer and winter time selection

Summer Model	λ	R^2	Winter Model	λ	R^2
NR[2]	18.98	0.87	NR[2]	4.89	0.90
NR[3]	18.97	0.87	NR[5]	3.88	0.92
NR[4]	18.79	0.87	NR[8]	3.34	0.93
NR[5]	18.77	0.873	NR[10]	3.09	0.94
NR[6]	18.77	0.873	NR[13]	2.99	0.94
NR[7]	18.34	0.876	NR[16]	2.82	0.94



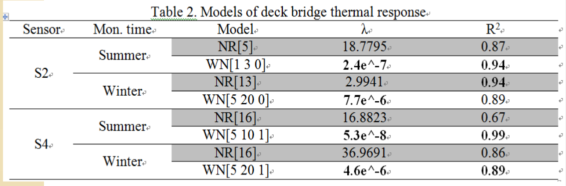


Table 2. Models of deck bridge thermal response

Sensor	Mon. time	Model	λ	R^2
S2	Summer	NR[5]	18.7795	0.87
		WN[1 3 0]	2.4e^-7	0.94
	Winter	NR[13]	2.9941	0.94
		WN[5 20 0]	7.7e^-6	0.89
S4	Summer	NR[16]	16.8823	0.67
		WN[5 10 1]	5.3e^-8	0.99
	Winter	NR[16]	36.9691	0.86
		WN[5 20 1]	4.6e^-6	0.89

the models shown in Table 2 are capability of modeling thermal response. Comparing the results for the NR and WN-NLARX models are shown in Table 2. From this Table, it can be concluded that the WN models are more suitable to predict the thermal response of Fu-Sui bridge; and the WN model can be used with abundant number of observations which are available with SHM systems.

Conclusions:

- From the time series analysis of the first year's monitoring data, it can be seen that the temperature variation on the bridge region is between +30 and -22°C.
- the maximum deflections for all monitoring points are correlated with the temperatures changes and the reaction of the deck material is a nonlinear reaction with temperature effects.
- The regression fit of strain variation with ambient temperature effect refers to that the slope for sensor S15 and is greater than that of slope sensor S16 by 66 and 62% in summer and winter.

Conclusions:

- The output only model identification design presents that the S16 thermal response is more nonlinearity than the S15.
- the NNRARMX [3] and [20] models are suitable to predict the thermal response of the bridge. In addition, it is clearly seen that the models' outputs are in conformity with the observations strain.
- the parameters of these models can be used with next year's monitoring data to detect and evaluate the health state of the bridge in winter and summer.
- the NNRARMX [5] model reflects the displacement of the bridge deck at point D10 under environmental loads, and this model can be used to detect the damage of the bridge in the future with next year's SHM data measurements.

Conclusions:

- The suitable models can be used are NR[5] for S2 and NR[16] for S4 in summer time. Also, the suitable models can be used in winter time are NR[13] and NR[16] for S2 and S4, respectively. It means that the response of bridge due to ambient temperature is nonlinear; and S4 strain model identification is not affected from the monitoring time effects, so the flange for the bridge deck is affected with the temperature variance in summer and winter by a same percentage; whereas; the winter time is more nonlinearity affected on the strain S2; and the low temperature effect is higher than high one on bridge behavior.

Conclusions:

- the selection WN-NLARX models in summer and winter for S2 and S4 strains are WN[1 3 0], WN[5 20 0], WN[5 10 1] and WN[5 20 1] of the bridge response due to temperature effects; and the models are capability of modeling thermal response. In sddition, the WN models are more suitable to predict the thermal response of Fu-Sui bridge; and the WN model can be used with abundant number of observations which are available with SHM systems.

Thank you for your attention