Bridge Monitoring, Control and Smart Improvement

Compared with other structure system, civil engineering structure is generally designed to be of large volume, high redundancy to carry operational load and to resist extreme events. Smart sensors and actuators are the good candidates for the improvement of structural reliability and robustness. Recent research works in BE at Tongji University that address bridge monitoring, control and smart improvement include: Vibration reduction performance test and analysis of cable dampers considering girder-cable-damper interaction; Vibration control of cable stayed bridge under construction using active mass damper; Mechanical behavior and damage evolution of suspenders in arch bridges; Acoustic emission technique for stay cable damage evolution monitoring; Novel image based approach for bridge and cable deformation measurement; FBG sensing for bridge strain and acceleration monitoring; PZT impedance measurement for concrete bridge local damage monitoring; Wireless vibration sensing system for bridge decentralized condition monitoring.

Vibration Reduction Performance Test and Analysis of Cable Dampers Considering Girder-Cable-Damper Interaction

Using mechanical damper is one of the most effective measures for vibration mitigation of long stay cables of large span cable stayed bridges. In the conventional design theory for cable damper it is assumed that the cable's ends are fixed. However, when the span of cable-stayed bridge becomes large and the structure becomes more flexible, the effect of girder vibration on cable damper performance may have to be taken into account.

Objective: Many cable-stayed bridges around the world have their stayed cables replaced due to corrosion problem. The problem has in fact led to a worldwide concern about corrosion damage evolution in stayed cables.

Approach: This study proposed a simplified theoretical model with cable, damper and girder is analyzed by complex mode method; and the longest cables of three cable-stayed bridges, with a span of 400, 650 and 1000m respectively, were simulated to show the effects of girder vibration.

Significant Result: The analyzed results show that the girder vibration reduces the effectiveness of damper as the cable length increases. Therefore, it is suggested that the girder vibration should be considered in cable damper design for longer span cable-stayed bridge.

Principal Investigator:

Dong Liang, Limin Sun, Wei Cheng, Hongwei Huang, Shijie Du

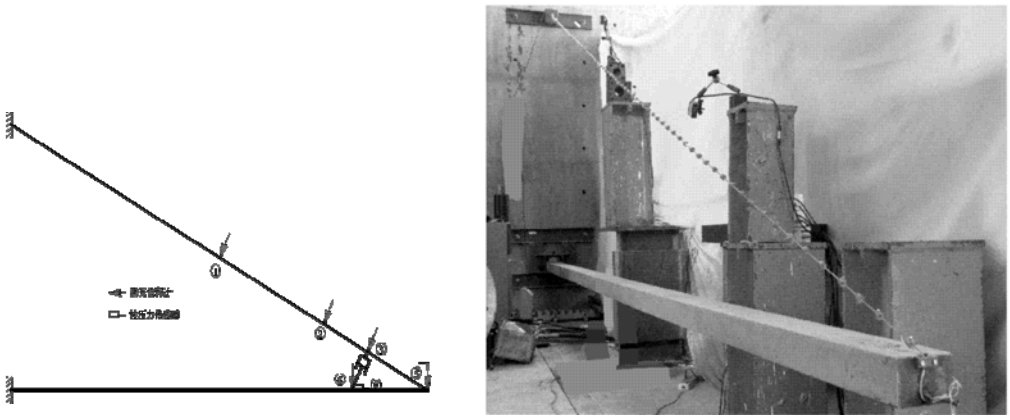
Funding:

National High-tech R&D Program (863 Program) of China (Grant No. 2006AA11Z120), National Natural Science Foundation (grant no. 50808063).

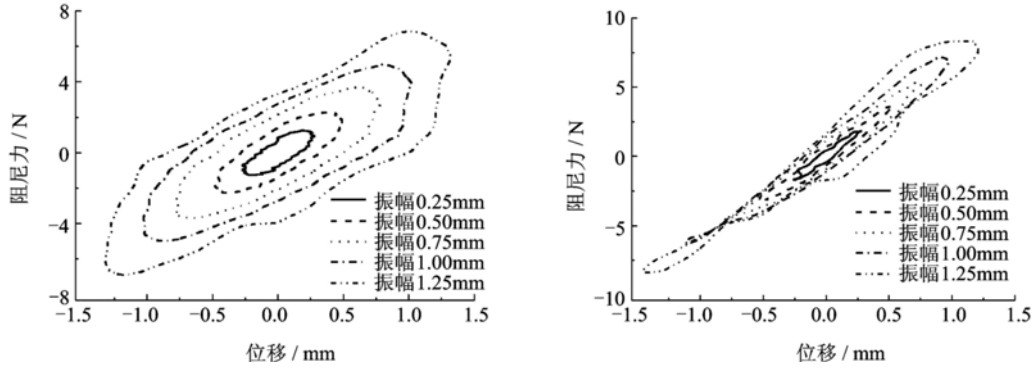
Key Publications:

Dong Liang, Limin Sun, Wei Cheng, Hongwei Huang, Effect of girder's vibration on performance of cable dampers for cable-stayed bridges [J]. *Chinese Journal of Theoretical and Applied Mechanics, 2009*, 41(4): 563-573.

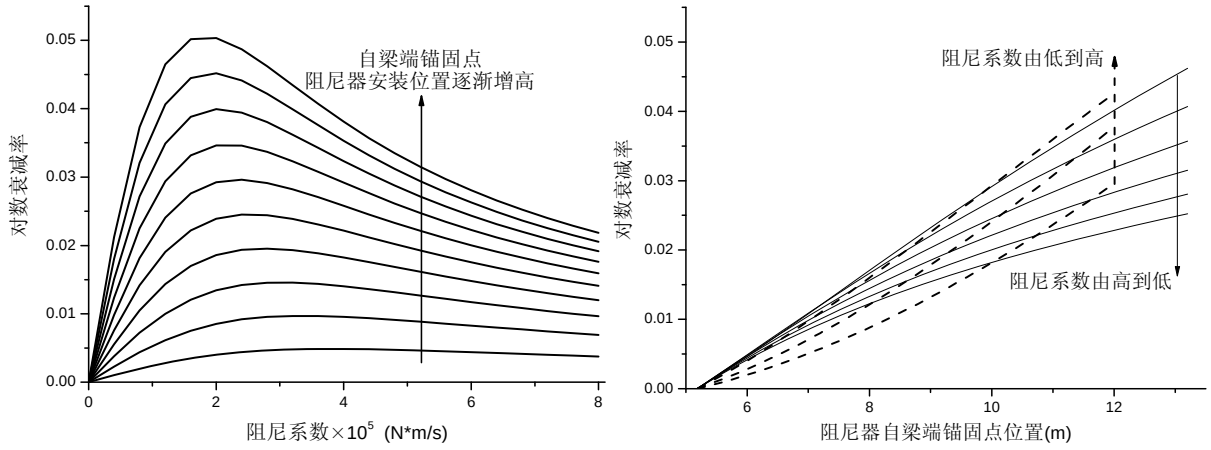
Dong Liang, Limin Sun, Hongwei Huang, Experiment on performance of cable dampers influenced by girder vibration for cable-stayed bridges [J]. *Journal of Vibration Engineering*, 2009, 22(1): 13-18.



The girder-cable-damper coupled vibration system and test setup



Tested hysteristics curve of a single viscous damper



Logarithmic decrement variety with damping coefficient

Logarithmic decrement variety with damper's position

Parametric study of vibration reduction performance considering girder vibration

Vibration Control of Cable Stayed Bridge under Construction Using Active Mass Damper

Although the vibration response of a fully erected cable-stayed bridge should be controlled, a cable-stayed bridge under construction, which is of low damping and not as stable as the completed structure, is generally more vulnerable to dynamic loadings. During the construction stage, the cable pylons were generally erected firstly and the cable and main girders are then hang on the pylons symmetrically in a double-cantilever way. With the increase of the cantilever length, the bridge is more and more flexible. When the girder is on its longest double-cantilever state, the bridge is the most vulnerable to the external disturbance (such as the ambient wind fluctuation and ground motions). Moreover, if the cables, pylons and main girder of the bridge are all steel components and thus the damping of the bridge is very low, its vibration under ambient excitations will be quite large. The vibration reduction countermeasures are thus in great demand.

Objective: A cable stayed bridge under construction has low structural damping and is not as stable as the completed bridge. Control countermeasures, such as the installation of energy dissipating devices, are thus required. In this study, the general procedure and key issues on adopting an active control device, the active mass damper (AMD), for vibration control of cable stayed bridges under construction were studied.

Approach: Taking a typical cable stayed bridge as the prototype structure; a lab-scale test structure was designed and fabricated firstly. A baseline FEM model was then setup and updated according to the modal parameters measured from vibration test on the structure. A numerical study to simulate the bridge-AMD control system was conducted and an efficient LQG-based controller was designed. Based on that, an experimental implementation of AMD control of the transverse vibration of the bridge model was performed.

Significant Result: The results from numerical simulation and experimental study verified that the AMD-based active control was feasible and efficient for reducing dynamic responses of a complex structural system. Moreover, the discussion made in this study clarified some critical problems which should be addressed for the practical implementation of AMD control on real cable-stayed bridges.

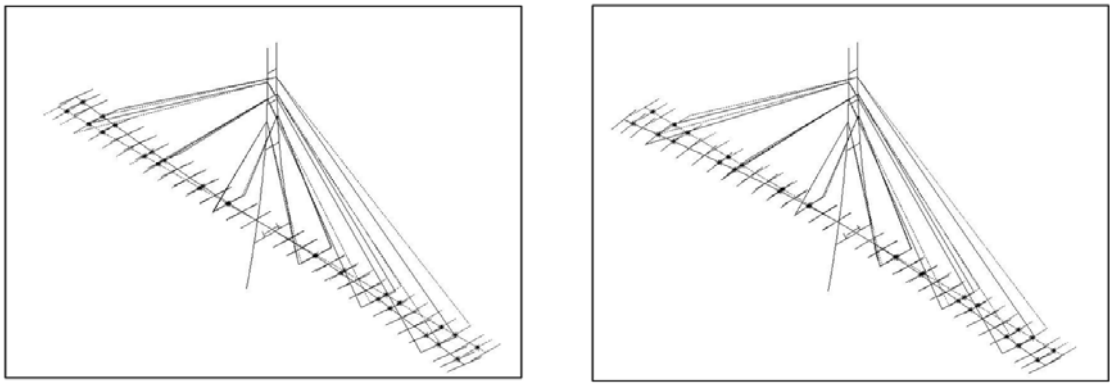
Principal Investigator:

Hao Chen, Zhi Sun, Limin Sun

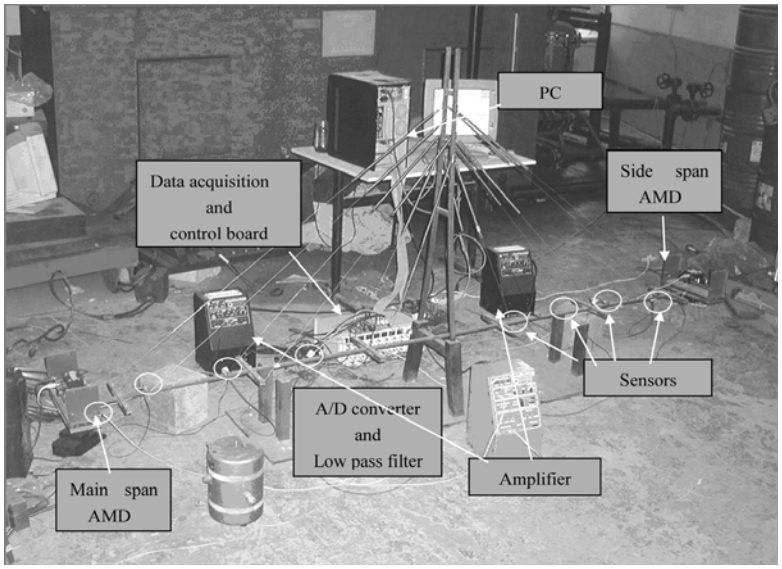
Funding: National High-tech R&D Program of China (863 Program) (Grant No. 2006AA11Z109), and New Century Talent Support Program of Ministry of Education of China (Grant No. NCET070623).

Key Publications:

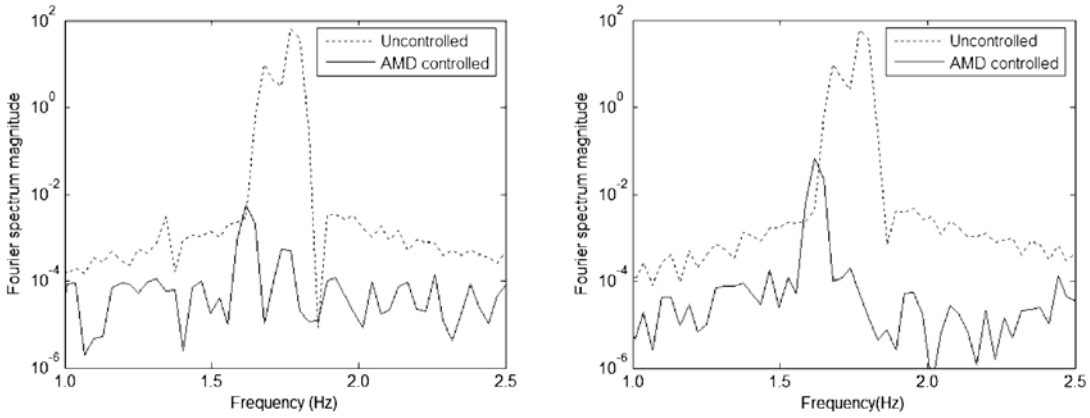
Hao Chen, Zhi Sun, Limin Sun. Active mass damper control for cable stayed bridge under construction: an experimental study [J]. *Structural Engineering and Mechanics*, 2011, 38.



The symmetric and anti-symmetric modes with the same resonant frequencies



Experimental setup of the AMD equipped cable-stayed bridge in construction



Vibration control performance

Mechanical Behavior and Damage Evolution of Suspenders in Arch Bridges

Bridge collapses occurred in recent years, while arch bridges with flexible suspenders occupied a large proportion of these events. Suspenders are one of the most critical and most vulnerable components for arch bridges, due to the lack of the systematic and reliable method to suspenders' health evaluation. The damage mechanism hasn't been studied deeply. Aiming at the application of structural health monitoring and evaluation for suspenders, the damage deterioration mechanisms for suspender are studied in this research program. Efforts and fulfillments are focused on the following issues: the mechanical behaviors and damage deterioration mechanisms of suspender; the nonlinear static behaviors of multilayered semi-parallel wire cables with symmetric/non-symmetric wire breaks under static tensile loads; and the stress redistribution and deterioration evolution of damaged suspender with broken wires.

Objectives The objectives of the research are to reveal the mechanical behaviors of suspenders under traffic loads and temperature changes, and damage deterioration mechanisms of suspenders in arch bridges. Also it is planned to find the evolution process of broken wires in the damaged suspenders.

Approach Experimental model tests are conducted to obtain the cable's responses due to temperature variation and deck vibration, as well as the stress redistribution and the force-displacement envelopes of cable with broken wires. Based on the experiments, theoretical derivation and refined finite element analysis are performed to obtain the damage model and the deterioration process.

Significant Results The damage mechanics of suspenders in arch bridges is obtained and a new damage model combining the real constitutive relations of wires, strength, stiffness, ultimate strain, corrosion and loading history is proposed for cables. A damage indicator of suspender is established. These fulfillments are helpful for both health monitoring and condition assessment of bridge suspenders.

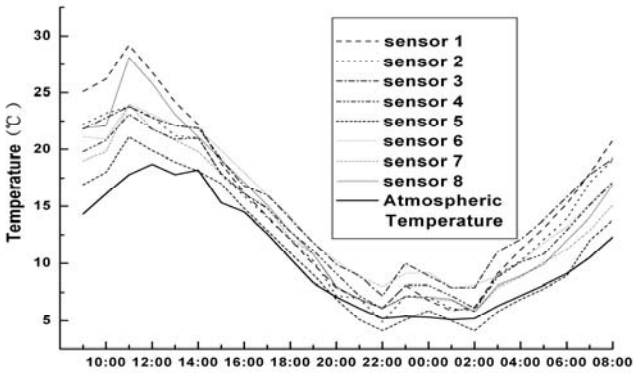
Principal Investigators
Qiwei Zhang, Jianfeng Liu, Yunfeng Ji, Yuanbing Li

Funding The National Science Foundation of China (Grant No. 50978199)

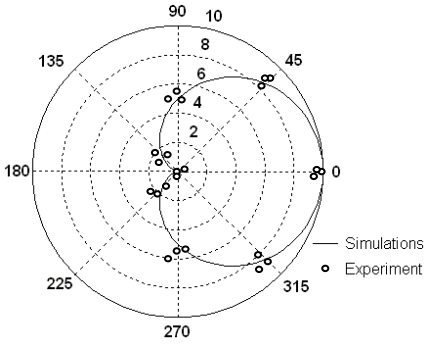
Key Publications

[1] Y.B. Li and Q.W. Zhang. The proposed damage model and mechanical behaviors of damaged short suspenders in arch bridges. The Sixth International Conference on Bridge Maintenance, Safety and Management. July 2012, Lake Como, Italy.

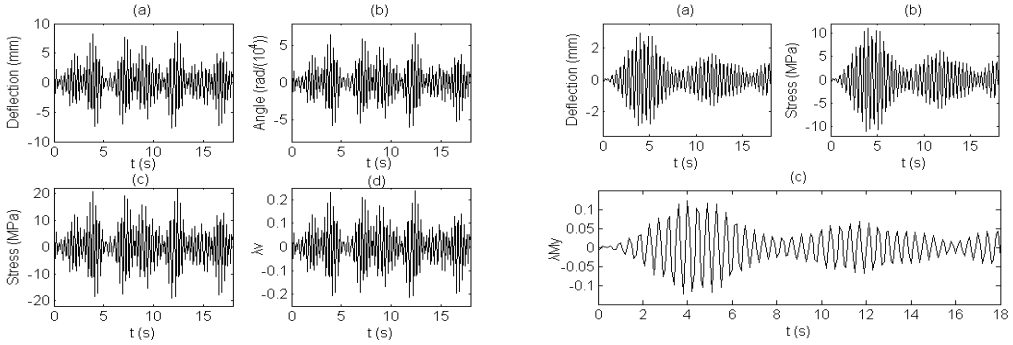
[2] Liu Jianfeng, Li Yuanbing, Bai Ping and Zhang Qiwei(2014), Mechanical Behavior of Damaged Strand Suspender with Symmetric Broken Wires in Arch Bridges. Journal of Tongji University, 42(4): 547-551



Variation of surface circumferential temperature of suspender

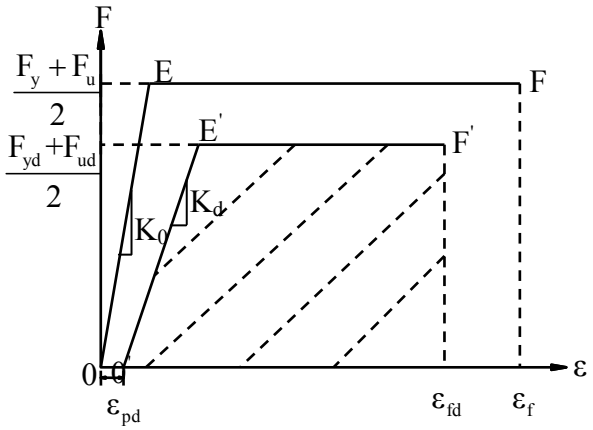


Distribution of ircumferential temperature difference of the suspender (unit:℃)

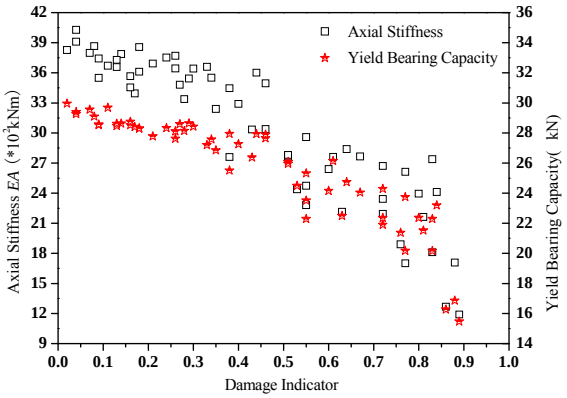


(a) (b)

Dynamic response of short suspender with (a) vertical vibration; (b) longitudinal vibration.



Bilinear approximation of proposed damage indicator for cable wires



Degradation of wires' mechanical properties with damage indicator

Acoustic Emission for Stay Cable Damage Evolution Monitoring

Surveys have pessimistically reported that some cable-stayed bridges are in danger mainly because of cable corrosion. With the unavoidable aging of stayed cables, monitoring the cable health to ensure proper performance of existing cable-stayed bridges cannot be separated from the bridge health monitoring system. Acoustic emission (AE), as a real time passive NDT technique, is of the potential to track the invisible damage evolution in the stay cables.

Objective: To simulate and analyze the acoustic emission waveforms for wire crack expansion, wire breakage and cable damages to obtain the baseline time frequency characteristics for cable damage evolution monitoring.

Approach: Through monitoring and processing the acoustic response in the cable, this technique can detect the sudden energy release due to cable wire breaking and thus can be used for cable damage alarming. Recent studies show that by analyzing the amplitude and frequency contents of the acoustic emission wave signal, the type of fracture mechanism and damage progression of the monitored cables can be determined. Following this idea, this study focuses on setting up baseline acoustic wave patterns for various types of cable damages through both numerical simulations and AE tests during large scale cable failure tests. The wave patterns due to the environmental noise, such as friction and impaction, are also investigated during the tests. During the pattern extraction, the wavelet analysis technique is used.

Significant Result:

The results illustrate that the obtained time-frequency distribution can be used to identify the modes of wave as well as the acoustic emission source characters. It also can be used to locate the acoustic emission source.

Principal Investigator:

Ting Jin, Ji Qian, Zhi Sun, Limin Sun, Yong Jiang

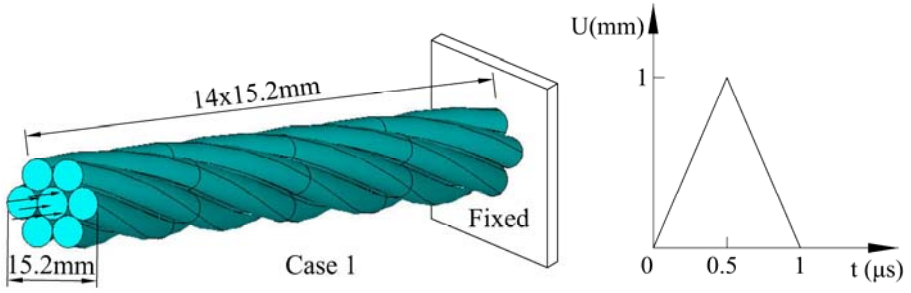
Funding:

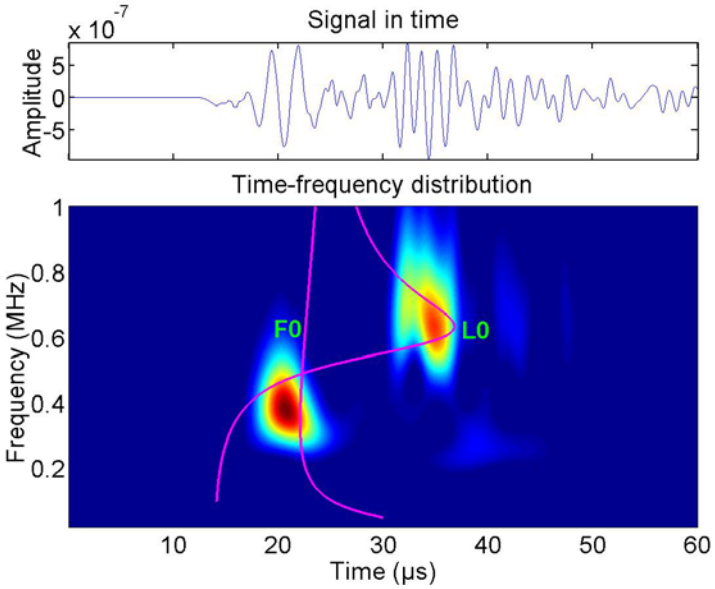
Natural Science Foundation (Grant No. 50538020).

Key Publications:

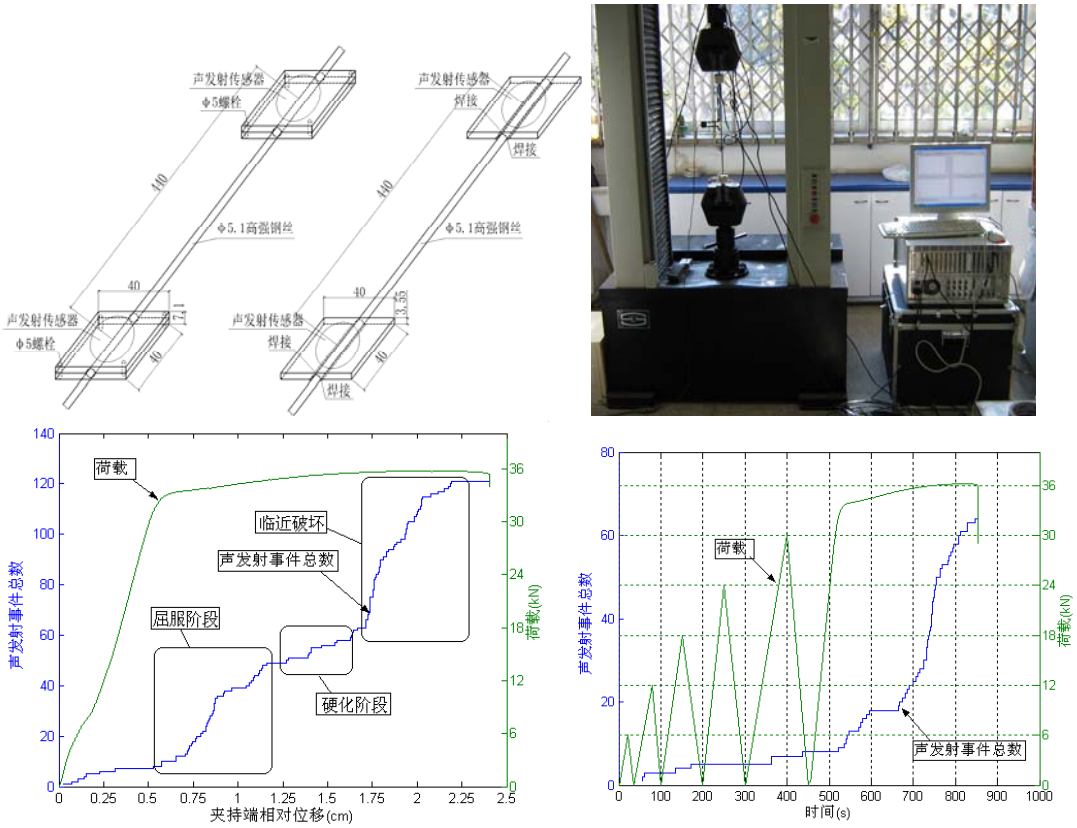
Ting Jin, Zhi Sun, Limin Sun. Modeling of Acoustic Emission Due to Crack Growth with Finite Element Method and Time-Frequency Analysis of the Signal [J]. *Journal of Vibration, Measurement & Diagnosis*, 2007, 27(4): 288-291.

Ji Qian, Limin Sun, Yong Jiang. Acoustic emission tests for high-strength wire breakage [J]. *Journal of Vibration and Shock*, 2014, 33(4): 54-59.





The simulated wave propagation measurement in seven-wire strand.



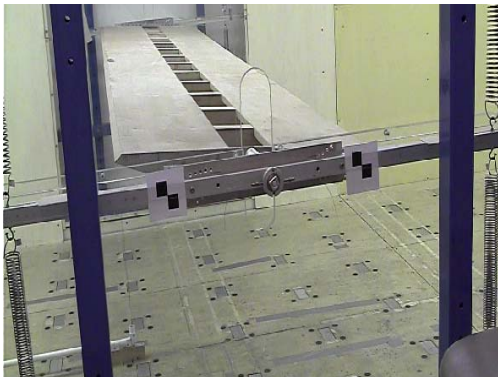
AE experimental setup and test results for steel wires in cyclic axial loading.

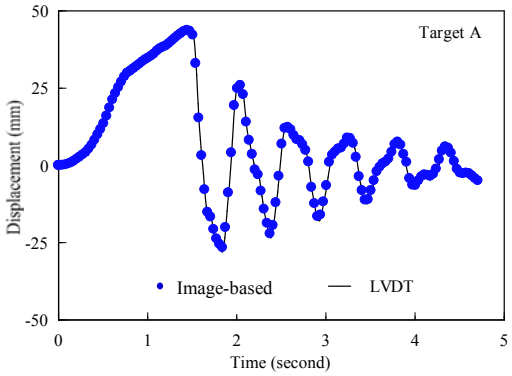
Novel Image-based Approach for Bridge and Cable Deformation Measurement

With the incessant advancement in optics, electronics and computer technologies during the last three decades, commercial digital video cameras have experienced a remarkable evolution, and can now be employed to measure complex motions of objects with sufficient accuracy, which render great assistance to structural displacement measurement in civil engineering.

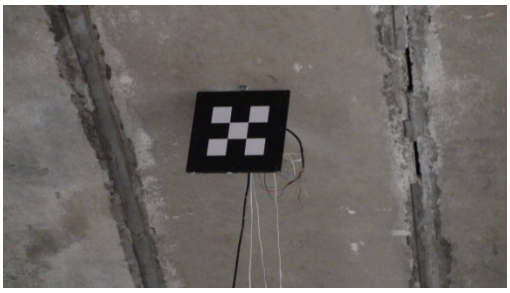
Objective: This study is aimed to develop image-based approach for flexible structure dynamic displacement measurement.
Approach: One digital camera is used to capture image sequences of planar targets mounted on vibrating structures. The mathematical relationship between image plane and real space is established based on computer vision theory. Then, the structural dynamic displacement at the target locations can be quantified using point reconstruction rules. Compared with other tradition displacement measurement methods using sensors, such as accelerometers, LVDTs and GPS, the proposed approach gives the main advantages of great flexibility, a non-contact working mode and ease of increasing measurement points. To validate, four tests of sinusoidal motion of a point, free vibration of a cantilever beam, wind tunnel test of a cross-section bridge model, and field test of bridge displacement measurement, are performed.
Significant Result: It can be seen that for displacement response of big amplitude, the results measured by the proposed technique are rather accurate compared with the LVDT data. This test also verifies that the proposed measurement technique has a great potential for the dynamic measurement in field applications.

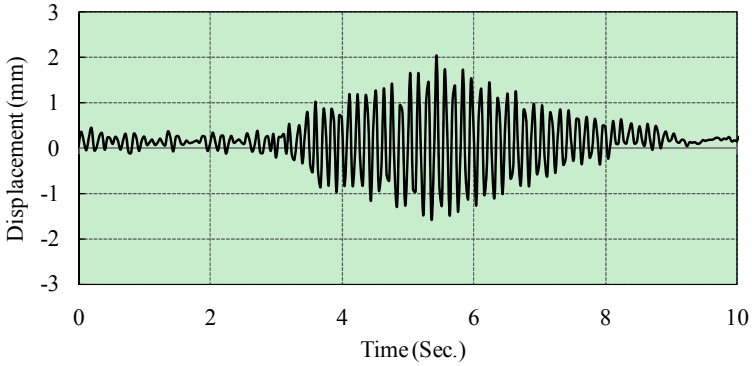
Investigators:
Y. F. Ji, Ning Hou, Q.W. Zhang, Zhi Sun, J.F. Liu, Qin Ye, Xiaoua Tong, and Shijie Liu
Funding: 863 program of Ministry of Science and Technology of China (Grant No. 2006AA11Z109), National Natural Science Foundation of China (NSFC) Grant 50908170.
Key Publications:
Ning Hou, Zhi Sun. Non-contact dynamic displacement measurement for stay cables based on videogrammetry Technique [C]. ***Proceeding of AESE 2007***, 2007.
Y. F. Ji and Q. W. Zhang, A Novel Image-based Approach for Structural Displacement Measurement [C], Bridge Maintenance, Safety, Management, Resilience and Sustainability, Stresa, Italy, 2012, 407-414.



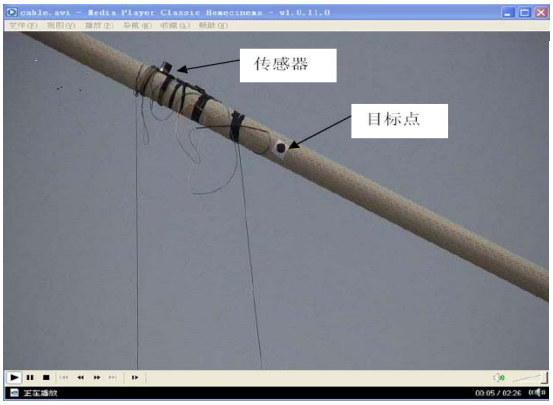


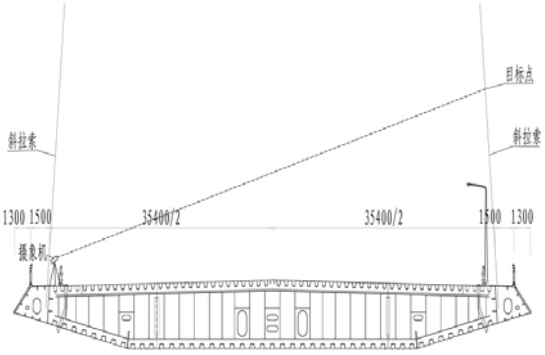
Measured response in wind tunnel test

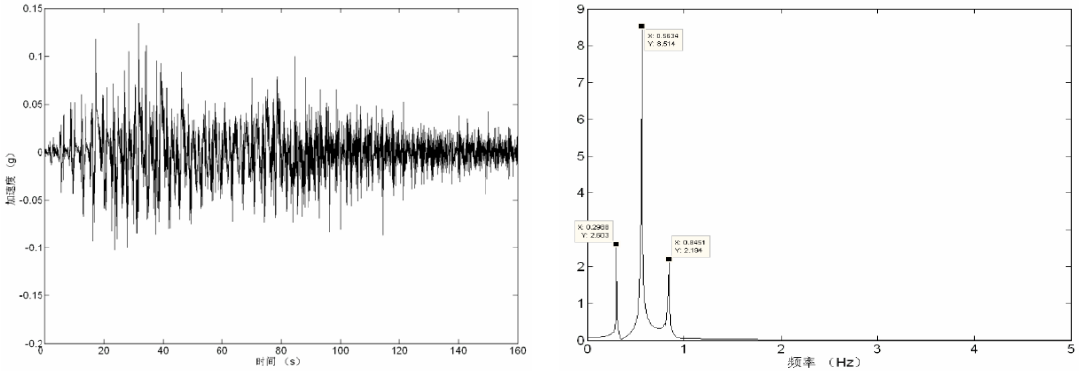




Measured displacement time history of the girder bridge in dynamic load test







On-site measurement of cable dynamic deformation on Sutong Bridge

FBG Sensing for Bridge Strain and Acceleration Monitoring

Thanking to its distinguishing advantages including wavelength multiplexing capability, miniature size, high sensitivity, immunity from electro-magnetic interference and etc, the fiber Bragg grating (FBG) sensing technologies are regarded as a competent candidate for the long-term bridge health monitoring. According to the shifted Bragg wavelength of the light reflected by a fiber grating, the FBG sensors can accurately measure various physical properties such as strain, temperature, displacement, acceleration and corrosion. One special advantage of the FBG sensing technology is that only one demodulation device is required to acquire various physical properties simultaneously. Compared with the bridge health monitoring system using conventional sensors, this advantage makes the distributed sensing possible and data transmission more convenient because many FBG sensors can be series connected by a single fiber. In this study, an integrated FBG sensing system is presented for monitoring the physical state of a real bridge.

Objective: To develop an integrated FBG sensing system for bridge stain and acceleration monitoring.

Approach: In this study, a FBG accelerometer is designed and fabricated to measure low frequency range acceleration signal. During the design, we infused a damping liquid with some viscosity into the mechanical structure and adjust it to make sure of a damping radio ξ=70%. Using this FBG accelerometer and FBG strain gauge, an integrated FBG monitoring system is developed and used for long-term measurement of Donghai Bridge.

Significant Result: The FBG accelerometer can show high performance over the frequency range $0< \overline{w} <0.6\ ^{w_o}$. The integrated FBG system have some high performances of workability and durability for bridge long-term monitoring.

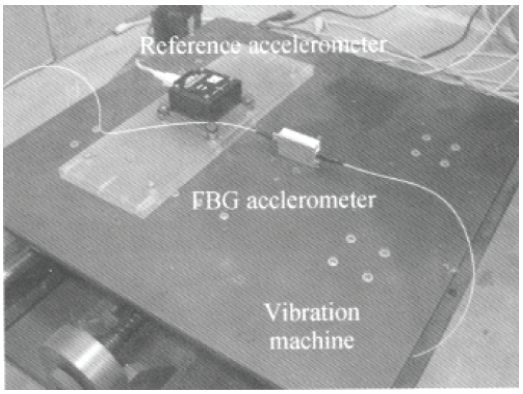
Principal Investigator:
Ru-Jiao Sun, Yang Shen, Li-Min Sun, Zhi Sun, Dan-Hui Dan

Funding: Key Research Program of Shanghai Committee of Science and Technology (No.03dz11003 and 04dz212041).

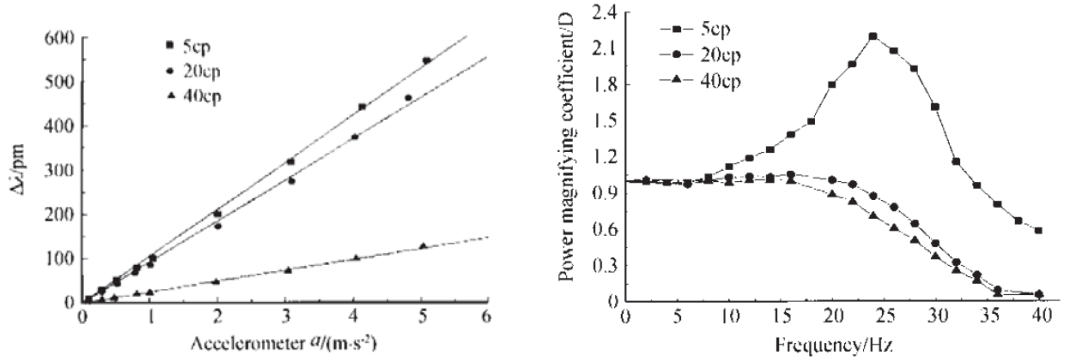
Key Publications:

Ru-Jiao Sun, Zhi Sun, Li-Min Sun. An integrated FBG sensing system for bridge health monitoring [J]. ***Proceeding of SPIE***, 2006, 6174-97.

Ru-Jiao Sun, Li-Min Sun, Zhi Sun, Dan-Hui Dan, Xiao-Hui Liu. Design Research of Fiber Bragg Grating Accelerometer [J]. ***Acta Photonica Sinica***, 2007, 63-67.



Calibration test of FBG accelerometer



Sensitivity, linearity, and amplitude-frequency test of prototype FBG accelerometer

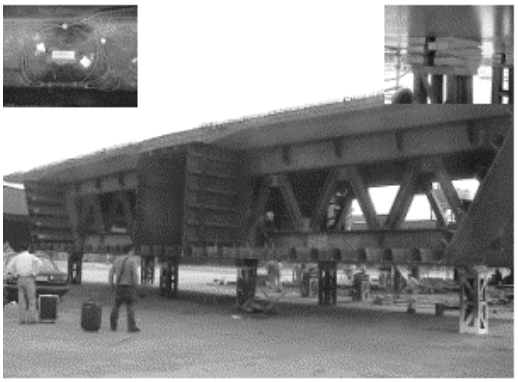


Figure 3: the mid-span segment on May 13

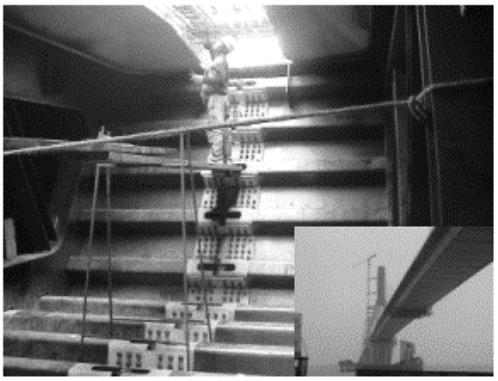
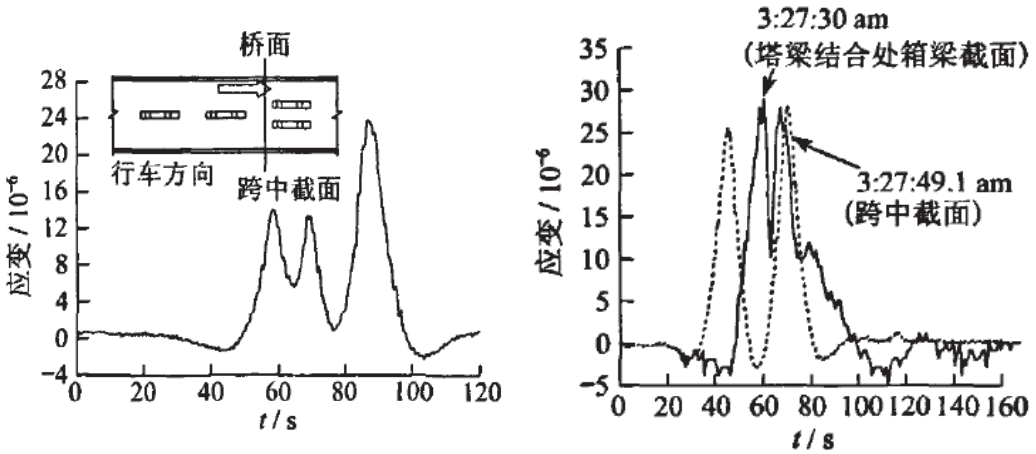


Figure 4: the mid-span segment on May 21



FBG strain measurement on the main navigation channel bridge of Donghai Bridge

PZT impedance measurement for concrete structure local damage monitoring

Concrete is the most widely used material for civil engineering structures. The way to monitor its compressive strength development is very important for ensuring the quality of concrete structure fabrication. Piezoceramic (PZT) based electromechanical impedance (EMI) method is a newly proposed idea for concrete monitoring.

Objective: This paper presented an experimental study on piezoelectric impedance based monitoring technique for the strength gain monitoring in concrete during curing process, the local damage monitoring in RC beam under step-by-step loading, and the prestress state monitoring of PC beam under different levels of prestress forces.

Approach: The piezoceramic (PZT) patch was attached on the concrete specimen to collect the monitoring signal. The EMI spectra of surface bonded PZT patch were collected using an impedance analyzer by sweeping the frequency. A regression analysis is conducted to establish the empirical relationship between the relative strength gain of concrete and the monitored relative resonant frequency change of the EMI spectra. The established empirical formula is used for concrete strength monitoring via EMI spectra.

Significant Result: It is seen that relative resonant frequency index and the relative strength gain have a strong correlation. In this study it is observed that the changes of resonant frequency from day 3 to day 14 are 14% for mix A, 6% for mix B and 8% for mix C, while the changes of gain in strength from day 3 to day 14 are more than 75%. The PZT impedance is in-sensitive to the local damage in concrete beam induced by step-by-step loading but will make an obviously frequency shift under different levels of prestress state.

Principal Investigator:
Zhi-Gang Guo, Zhi Sun

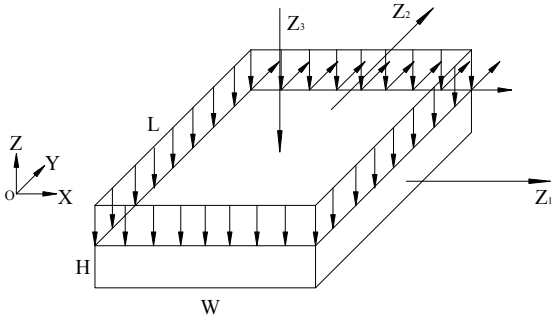
Funding: Rising-star program of Shanghai Commission of the Science and Technology (09QH1402300). Independent research program of state key laboratory for disaster reduction in civil engineering (SLDRCE09-B-15).

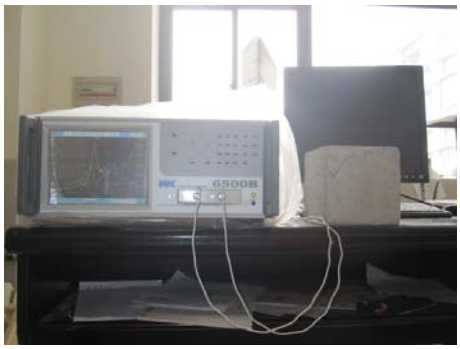
Key Publications:

Zhigang Guo, Zhi Sun. Piezoelectric Impedance Based Elastic Modulus Monitoring for Concrete during Curing [C]. Yantai, China: Trans Tech Publications, 2012, 166-169: 969-973.

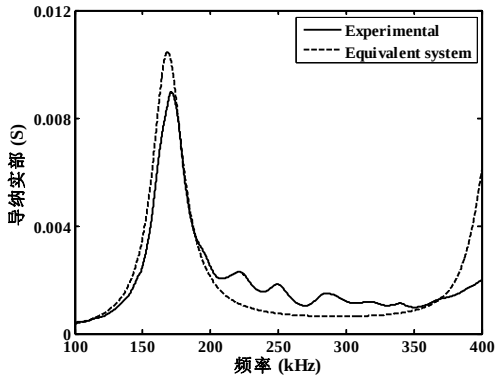
Zhigang Guo, Zhi Sun. Piezoelectric Impedance Based Strength Gain Monitoring in Concrete [C]. San Diego, California, USA: SPIE, 2012, 8345: 8345A.

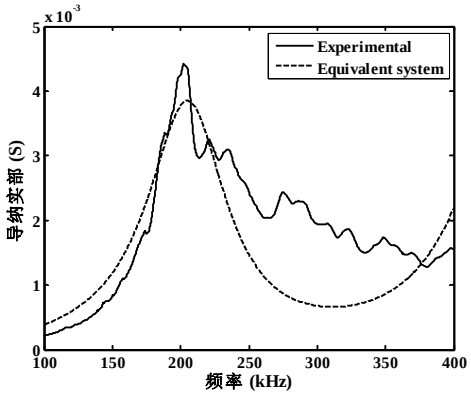
Zhigang Guo, Zhi Sun. Piezoelectric Impedance Based Prestress Force Monitoring for PSC Beam [C]. International Conference on Civil Engineering and Building Materials, Kunming, China on July 29-31, 2011.



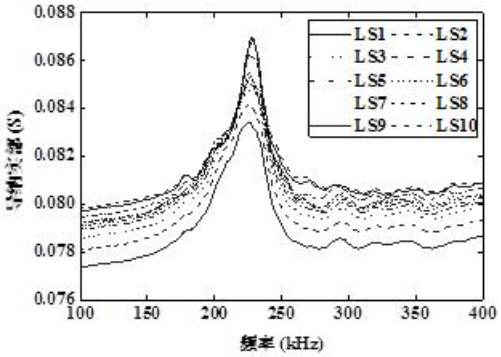


PZT impedance test of concrete cube

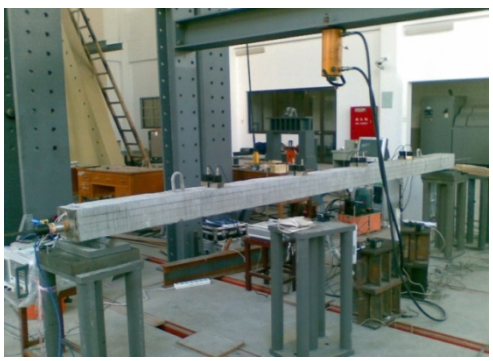


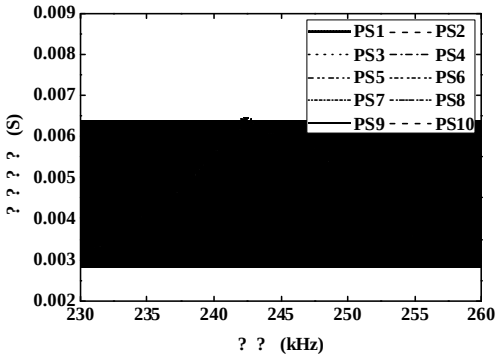


The measured and re-constructed admittance spectrum



Loading tests of RC beam and the PZT admittance measurement





Prestress process tests of PC beam and the PZT admittance measurement

Wireless vibration sensing system for bridge decentralized condition monitoring

The recent rapid development of wireless sensing and communication techniques, the research on structural decentralized health monitoring attracts more and more attention among vibration based structural health monitoring community. Compared with the traditional centralized methods, the decentralized methods process the data collected by limited number of neighbor sensors among the local subgroup, extract the meaningful information of compressed size, and then send the extracted information back to the central station for further analysis and final decision making. Therefore, it will greatly reduce the time, labor, cost and complexity on data transmission and centralized multiple channel signal processing and decision making. Concerning that each distributed local processor only requires limited resources to process the limited data among the local subgroup, the total processing time and cost are thus greatly reduced.

Objective: This study developed a decentralized health monitoring study for beam-like structures with a lab verification using wireless acceleration measurements.
Approach: According to structural geometrical layout, the structure is divided into multiple local subgroups firstly. Based on vibration test within each subgroup, structure dynamic flexibility matrix of each measured subgroup is estimated and structural damage locating vector is computed. Structural damage location can then be detected among each subgroup. The final decisions on structure damage occurrence and location are made by comparing the results obtained from different subgroups. Both numerical and experimental studies on a beam-like structure are conducted to demo the procedure.
Significant Result: The results tell that both the distribution and the level of the parametrical modeling error will have some influence on damage diagnosis conclusions. If the signal is polluted by noise, the condition will go worse. For the physical modeling error, it seems that the physical modeling of the baseline structure as a frame model with rigid connection will change the value of NCS but will not affect the result of damage diagnosis if the damage level is set to be 20%.

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Key Publications:

Ru-Jiao Sun, Zhi Sun, Li-Min Sun. An integrated FBG sensing system for bridge health monitoring [J]. ***Proceeding of IABMAS***, 2012, 6174-97.

Ru-Jiao Sun, Li-Min Sun, Zhi Sun, Dan-Hui Dan, Xiao-Hui Liu. Design Research of Fiber Bragg Grating Accelerometer [J]. ***Proceeding of IWSHM*** 2013, 63-67.

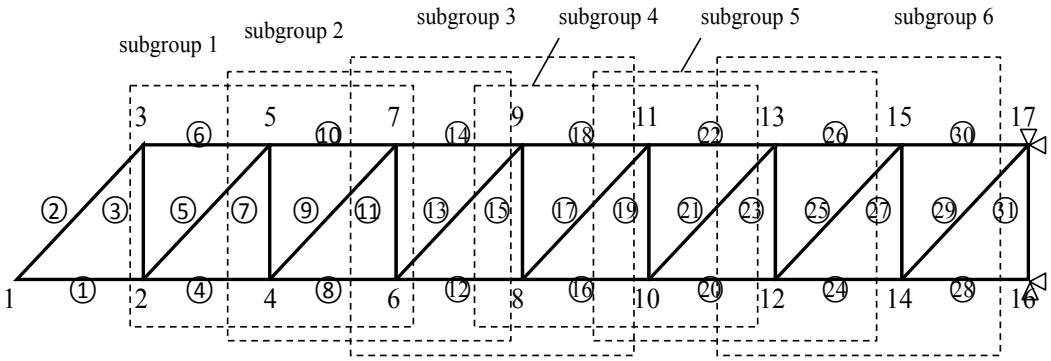
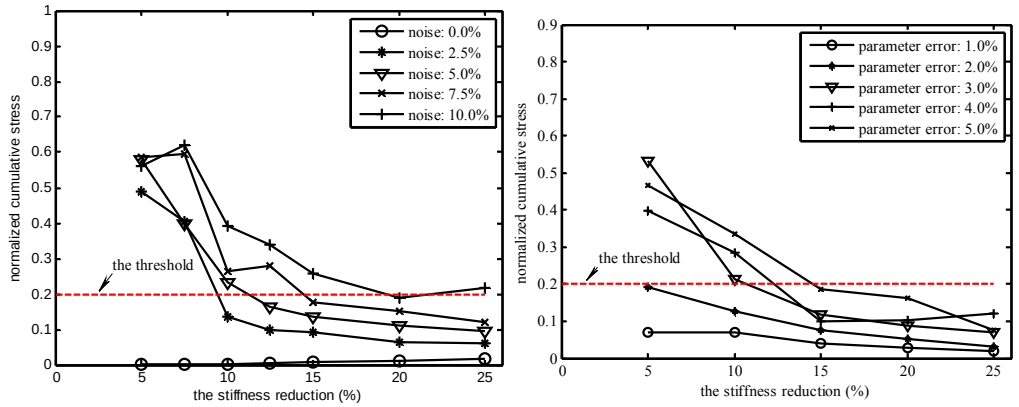
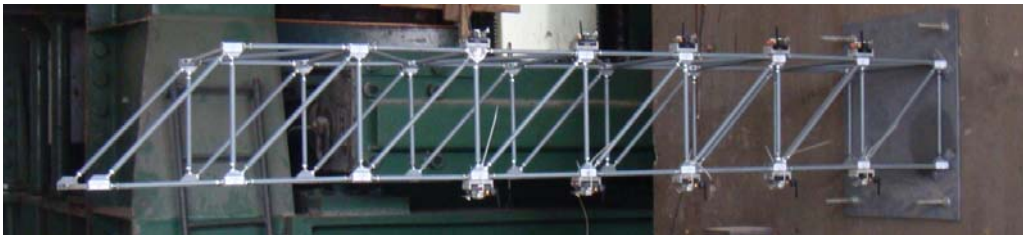
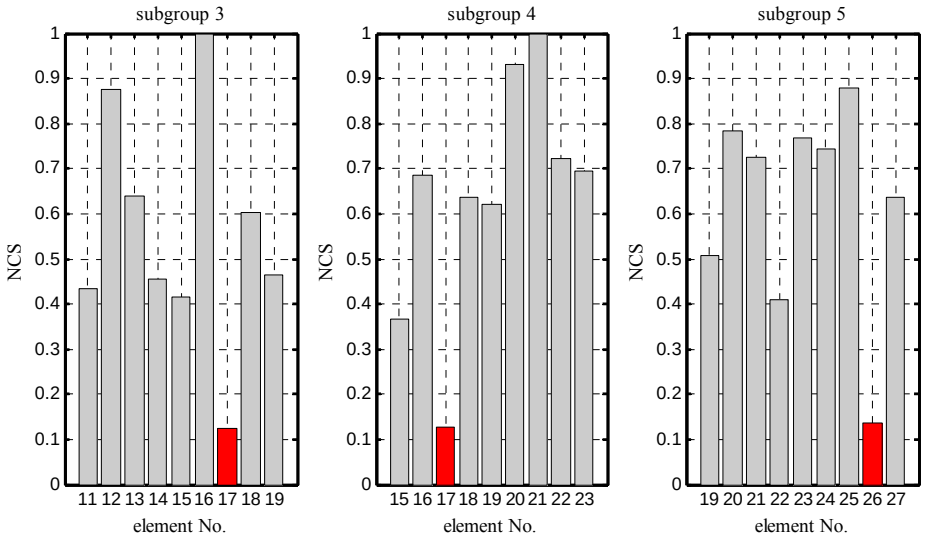


Figure 1. The planar beam-like truss model and the formed subgroups



Modeling error and noise effect on damage diagnosis accuracy





Experimental setup and results