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VULNERABLE COMPONENT MONITORING: A NOVEL CONCEPT FOR HEALTH MONITORING OF COMPLEX STRUCTURES

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Abstract

The recent engineering applications on health monitoring of large scale structures show that although thousands of sensors were installed on a structure and a great amount of data was collected daily from the monitoring system, it is still of great difficulty to give an accurate alarm on structural damage, as well as to precisely assess its physical condition. This made the structural authorities doubt whether it is valuable to invest so much on such an ambiguous system. In this paper, a novel structural health monitoring concept is proposed to show an alternative way that can address this problem. Concerned that the structures of different geometries and layouts will show different mechanical behavior, structural topological vulnerability analysis is conducted firstly. Based on this analysis, structural key components and failure modes can be obtained. After that, structural vulnerability analysis under different types of loading is conducted to determine the most vulnerable failure modes. Through the successive monitoring of the corresponding components, the safety of structural system can be ensured. This procedure will greatly reduce the blindness during the conceptual design of a health monitoring system. A case study on a cable-stayed bridge is conducted to demonstrate the procedure of the proposed methodology.

INTRODUCTION

Heavy loss due to the recent collapse of civil infrastructure strengthens the importance of developing applicable techniques for early-stage damage detection and health monitoring for bridges. For this purpose, some bridge health monitoring (BHM) systems were developed and installed on some long span bridges to collect the excitation and response signals for structural damage alarming and diagnosing, safety evaluation and condition assessment, and maintenance strategies determining [1]. However, if the sensing contents and sensor locations are not carefully determined, the collected information will be not efficient to embody a structural healthy condition. The achievement of these systems will be greatly limited. A logical way to solve this problem is to put more research attention on the preliminary design of a BHM system. The task of the design of a BHM system is to choose the monitoring contents, determine the sensor placement, and guide the system operation. All these functions are fulfilled using the data gained from the sensors, so the optimization of the sensor localizations should be carefully conducted. Structural vulnerability analysis is regarded as an efficient tool to help determine appropriate measurements and locations for structural monitoring.

Structural vulnerability, which is defined as the ratio between the local damage and the consequences of that damage to a structural system, is an opposite concept of robustness which means the capability to resistant disproportionate collapse. The collapse of the World Trade Center in New York, is a dramatic example which is partially due to the lack of enough structure robustness. This collapse also aroused the international research interest on structure vulnerability analysis once again.

The study on structural topological layout for structural vulnerability assessment is one of the research focuses. Woodman and his colleagues conducted a systematic research on structural vulnerability analysis [2]. Through identifying structural rings and rounds, they try to create a hierarchical description of the structure firstly. Structural vulnerable scenarios can then be identified by searching through the structural hierarchy. Liu and Liu presented an in-depth research of structural vulnerability analysis on a three-dimensional truss [3]. In this paper, they analyzed structural topology vulnerability firstly by evaluating structural redundant connection matrix. An approach to reveal structural vulnerable failure scenarios is then developed based on the system strain energy and redundant connection matrix in consideration of force redistribution.

The assessment of structural vulnerable components under extreme loading cases, such as the seismic loadings, is another related research topic. Hwang et al. [4] developed an analytical method to obtain the fragility curve of the concrete bridges under earthquake considering the uncertainties due to seismic ground motion, local site condition and bridge physical characteristics. Butenweg and his colleagues of the Aachen University of Technology conducted a series of research related to structural seismic vulnerability analysis. They defined vulnerability as the possible damage sustained by the building from a potential external influence [5]. Based on this definition, they presented a three-level methodology for the seismic evaluation of existing standard occupancy buildings. As a case study, the seismic vulnerability assessment of the Aachen Cathedral which was built in a seismic active region was presented.

In summary, it can be seen that research on structural vulnerability are still underway and that the uniform theory has not been formed yet. In this paper, a general scheme for structural vulnerability analysis is proposed below. The vulnerability analysis based conceptual design of the sensory subsystem is then presented. Finally, the application of the methodology on the health monitoring system design is illustrated on the main navigation channel cable-stayed bridge of the Donghai Bridge.

METHODOLOGY

Structural safety includes two levels of meaning: the component level safety and the system level safety. The failure of a single component may or may not mean the failure of the whole structural system. Structural vulnerability analysis is the study on identifying those components whose failure will fatally induce the failure of the whole system. Herein, the term “failure of a single component” implies the occurrence of a load effect that exceeds the capacity of the considered component. The failure of the structural system means that the maximum deformation or stress of the structure overpasses some preset limit value or some necessary connection is lost and a mechanism is formed. The structural failure modes due to the loss of stability are not considered in this study.

An ideal structural vulnerability assessment procedure should involve a structural topological analysis for the determination of structural key components, a structural mechanical analysis under different types of extreme loadings for the determination of structural vulnerable components, and a system-level evaluation of structural vulnerability concerning the above analyzing results.

Structural Topological Vulnerability Analysis

For a given structural system, the first step is to setup a vulnerability analysis model according to the topology layout and mechanical characteristics of the structure. In this study, all components are classified into two classes according to the connection relationship: the key components and the secondary components. The components, whose failure will induce disconnection of the structural system, are called the key component. The components, whose failure will not destroy the accessibility of the structural system, are called the secondary component. For safety evaluation, if the key components fail, the structural system is regarded to be failed. If the secondary components fail, a further check whether the key components will also fail in consequence should be performed. If the failure scenarios of the secondary components induce the failure of the key components, the connectivity of the structural system is destroyed. These secondary components are critical for structural vulnerability.

Structural Vulnerability Analysis under Extreme Loadings

The second main aspect of a vulnerability analysis is to get the vulnerable components of a structure under different types of extreme loadings. For the vulnerability assessment, the result of structural topology analysis is only an inner factor; it must interact with the specified loading types. The performance of a component will be differently exposed to different loads which include the man-made hazard of terrorism. (e.g., a “T” beam designed as the superstructure of a bridge can be easily destroyed under the lateral impact, because it was originally designed to support vertical loads).

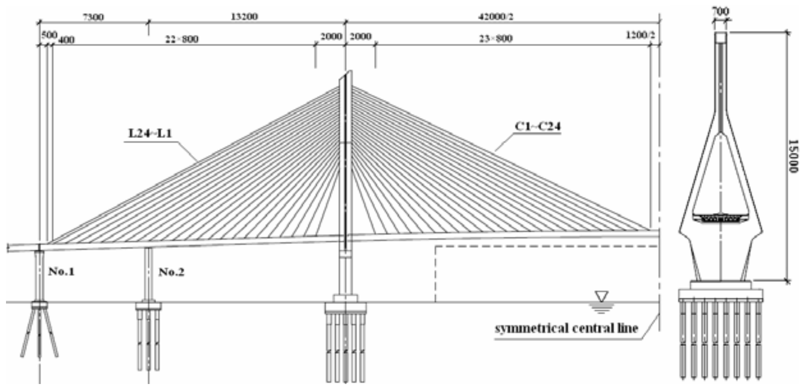
Vulnerability Analysis Based Sensory System Design

During BHM system design, the first and the foremost step is to optimize the sensory system. This step includes two items: choosing the appropriate type of sensors and optimizing sensor locations. Structural vulnerability assessment can expose the key components which have the fatal influence to the whole structure and the vulnerable components which have the high sensitivity to specified excitations. If the vulnerable components are found, the monitoring sensor can be determined according to component mechanical properties, material type and environment condition where it’s located. Considering that the monitored components are critical for structural performance, the collected information from the monitoring system will be useful for online damage alarming and offline structural condition assessment.

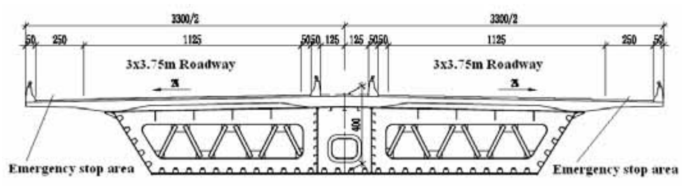
CASE STUDY

Description and FEM Modeling of Donghai Main-Navigation-Channel Bridge

The Donghai Bridge is a linkage connecting the Luchao port in Shanghai and the Yangshan Island deep water port. The linkage is about 32km long and consists of 2 cable-stayed bridges and a large number of spans of continuous and simply supported bridges. It crosses the East China Sea and is the longest bridge over the sea in China. Its main-navigation channel bridge is a two pylon single plane cable-stayed bridge with composite girders as shown in Fig. 1. The pylons are 150m tall in inverted Y shape made with reinforced concrete. The main span is 420m long.



a. the layout of the bridge and the pylon



b. the cross section of the main girder

Figure 1. General Information of the Main-channel Bridge (Units: cm)

A three-dimensional FE model of the main-channel cable-stayed bridge was setup in ANSYS. The pylons and the girder were simulated using 3D beam element. Cables were simulated using 3D bar element which can bear tension only. Some rigid beams were used to connect the girder with the cables. The mass and stiffness are carefully assigned to be equivalent to the actual structure. The six DOF's at the bottom of pylons were all fixed and additional vertical restraints were added to simulate the restrains from the assistant piers. The constructed FE model is shown in Fig. 2.

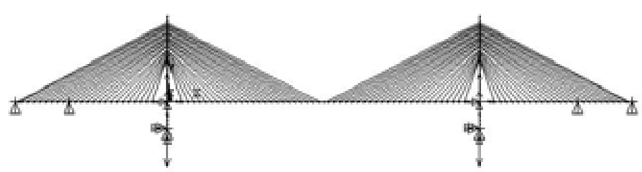
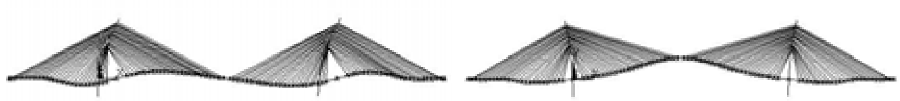


Figure 2. The FE Model of The Main-channel Cable-stayed Bridge

Conducting the eigenvalue analysis on the FEM model, the modal parameters of the bridge can be obtained. Figure 3 shows the modal parameters of the first eight modes of the bridge.



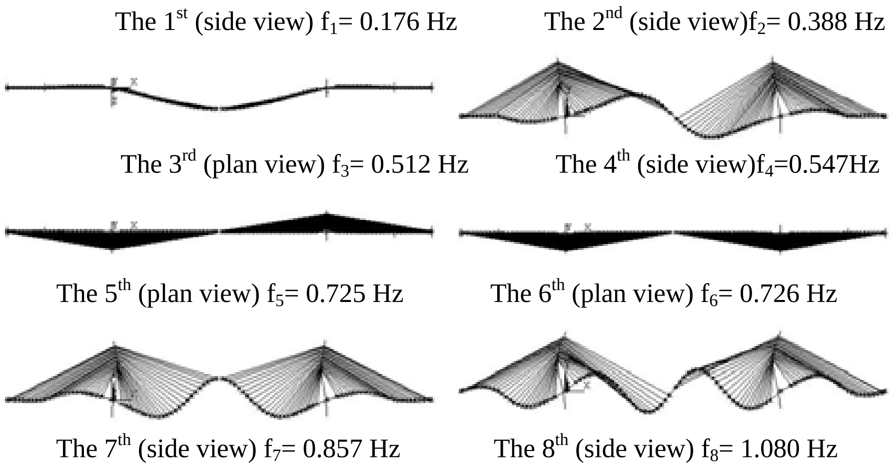


Figure 3. Computed Mode Shapes of the Donghai Main-channel Bridge

Topological Vulnerability Analysis

In order to systematically analyze the influence of the component failure to the structural system, a reasonable vulnerability analysis model is the sticking point for this analysis. In this study, the vulnerability analysis model is setup by checking the connecting relationship of the components one by one. If a component is connected in series in a structural system, its failure will destroy the force transmission path of the structural system. These components are regarded as the key components of the system. If a component is connected in a structural system in parallel, its failure is not so critical to the connectivity of the structural system. These components are regarded as the secondary components of the system. For a structure of legible force transmission path, such as the cable-stayed bridges, their vulnerability analysis models are easily available. However, for a structure with a complex layout, it will be very difficult to setup a vulnerability analysis model to describe them. During the determination of a structural vulnerability analysis model to a legible force transmission route structure, the following principles must be followed:

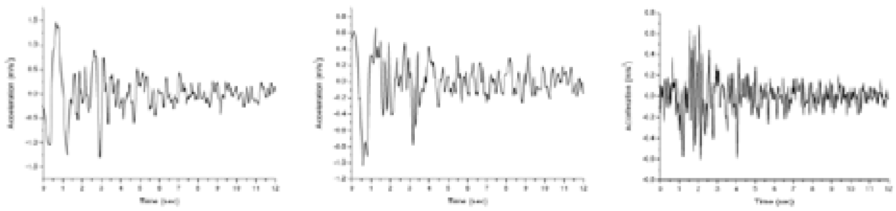
1) Each component in structure has only two statuses: operation or failure.
2) The structure has two statuses too: operation or failure.
3) If all the components are in operation, the structure is in operation.
4) If all the components are failed, the structure will be failed.

Figure 4 is the vulnerability analysis model for a cable-stayed bridge. The rectangle in the figure means the operation of components. If the connection between the input and the output was shut off by removing quite a number of rectangles, it means the failure of the structural system. Considering that the failure of the pylons and the main girder will cut the access of the system, they are regarded as the key components of a cable-stayed bridge. Since the failure of a single cable or single assistant pier will have no influence on the connectivity of the system, the cables or the assistant piers are the secondary components of the structural system.

Seismic Vulnerability Analysis

As a demonstration of the second step, the seismic vulnerability analysis of the bridge is conducted in this study. Based on the topological model proposed in the above section, the pylon, as the key component of the bridge, was studied to evaluate its vulnerable part. Moreover, the cable system, as the main supporting part in the force transmission path, should also be assessed to check the vulnerability of each cable pair under the external loadings.

To distinguish the vulnerable components of the bridge under the seismic loadings, a series of time history analysis were conducted on the FEM model. During the analysis, all components were assumed to be in its elastic working range. A twelve-second seismic acceleration record obtained from the ground acceleration measurements of Tianjin 1976 earthquake is used as the excitation record (as shown in fig.4).



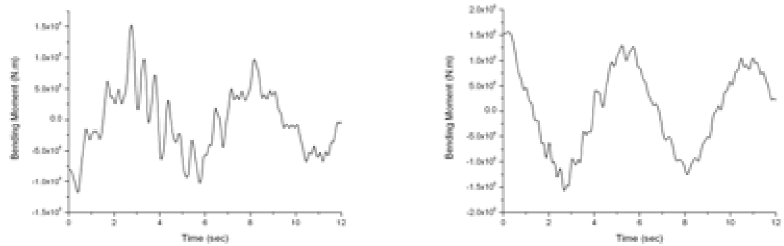
Longitudinal input Transverse input Vertical input

Figure 4. Seismic Excitation Time Record

A series of time history analysis were then carried out in ANSYS to check structural internal forces under the loading cases defined in the China code of “Specifications on Earthquake Resistant Design for Highway Engineering” [6]. The loading cases were listed in Table 1. During the analysis, the modal superposition technique is adopted for the response computation and 50 modes were taken into account. Fig. 5 shows the computed time history of the bending moments at the bottom section of the pylon under the loading cases EL and ET respectively. Fig. 6 shows the displacement time history at the tip of the pylon under the loading cases EL and ET respectively.

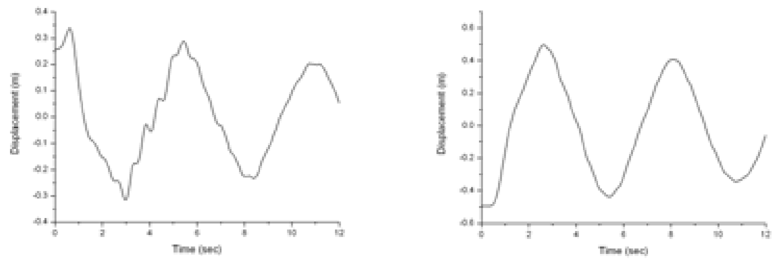
Table 1. Loading Case Scheme

Load Case	Combination	Description
DL	-	Dead load
EL	-	Seismic input in longitudinal direction
ET	-	Seismic input in transverse direction
EV	-	Seismic input in vertical direction
ELV	1.0EL+0.67EV	1.0 longitudinal seismic input + 0.67 vertical seismic input
ETV	1.0ET+0.67EV	1.0 transverse seismic input + 0.67 vertical seismic input
ELVMax	MAX(ELV)+DL	Max (combination of dead-load and longitudinal seismic load)
ELVMin	MIN(ELV)+ DL	Min (combination of dead-load and longitudinal seismic load)
ETVMax	MAX(ETV)+ DL	Max (combination of dead-load and transverse seismic load)
ETVMin	MIN(ETV)+ DL	Min (combination of dead-load and transverse seismic load)



a. Under longitudinal seismic input b. Under transversal seismic input

Figure 5. Bending Moment Time History at the Foot of the Pylon



a. Under longitudinal seismic input b. Under transversal seismic input

Figure 6. Displacement Time History on the Top of the Pylon

Concerning that the pylons are the key components to withstand the inertial forces due to the earthquake; its safety is specially checked. Fig. 7 shows the distribution of the maximum bending moment along the height of the pylon. In these cases, the bottom section of the pylon is the most vulnerable section as shown.

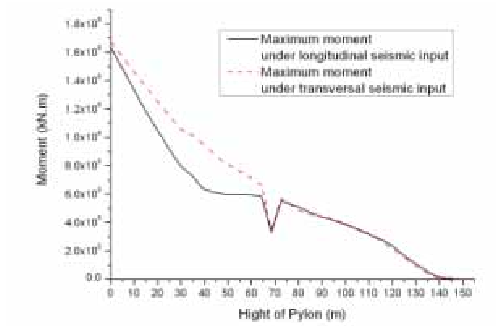


Figure 7. Maximum Moment Distribution in Pylon

The cable supporting system, as another key portion in the load path of a bridge, is also checked. Fig. 8 shows the maximum tensile stresses distribution under the given seismic excitations. As shown in the figures, in the side span, the longer cables (L18-L24) are more vulnerable to the given excitations. However, in the central span, the cables (C1-C2) close to the pylon are more vulnerable.

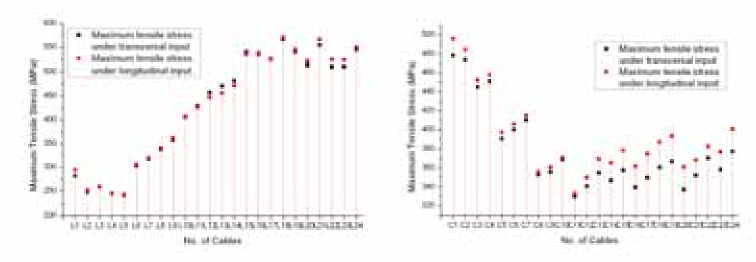


Figure 8. Maximum Tensile Stress in Cables

Sensory System Design

In this case study, since the bottom section of the pylon and cables L18-L24 and C1-C2 are the most vulnerable components to the seismic loadings, the strain gauges or cable force sensors should be installed to monitor the performance evolution of these components. According to the related investigations on cable diseases, cable diseases can generally be classified into four items: cracks on sheathing of stay cable; corrosion of Anchor Chain Terminal; corrosion and relaxation of cable steel wire; and crack of steel wire. So the sensors for cable monitoring should be of the capacity to address the problems above. Some items can be monitored using sensors, but others still have to be checked via visual inspections.

For the bottom section of the pylon, its importance has been emphasized in the design procedure, so it has enough safe redundancy to resist the design load. Then the concrete durability under environmental attack will be an important item which should be monitored. Therefore, a corrosion exposition station should be established at the bridge site, which has a similar ocean environment to the bridge. The state of corrosion can then be monitored through test samples which are exposed to the environment in the station. The electrochemistry measurements and strength tests should be regularly carried out to obtain data and relationships between corrosion, condition, and environmental factors.

CONCLUSIONS

In this study, a three-step structural vulnerability assessment technique is proposed. It involves a structural topological analysis for the determination of structural key components, a structural mechanical analysis under different types of extreme loadings for the determination of structural vulnerable components, and a system-level evaluation of structural vulnerability concerning above analyzing results.

In the step of structural topological vulnerability analysis, the analysis model proposed here is only applicable to those structures which have a legible force transmission route. For a more complex structure, a systematical mechanism generation method to find all possible failure modes of the structure is more reasonable. The related research is underway and will be reported in some future papers.

On the second step, this paper specially focuses on determining structural vulnerable components under seismic loadings. Through a time history analysis on the FEM model of the Donghai Main Navigation Channel Bridge, the vulnerability of pylons and cables of the bridge to the seismic loads is discussed. The analyzed results can be used for guiding the sensor placement. One thing that must be mentioned is no nonlinear effect is taken into account in this study and the uncertainties due to seismic ground motion, local site condition, and bridge modeling is not considered. Those factors will be carefully discussed in some upcoming papers.

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