Istanbul Bridge Conference
August 11-13, 2014
Istanbul, Turkey

New Statistical Pattern Recognition Technology for Condition Assessment of Cable-stayed Bridge under Earthquake Load

S. H. Lee[1] , G. H. Heo[2] and S. G. Seo[3]

ABSTRACT

In spite of its usefulness as a tool for monitoring health of structures under steady external load, the statistical pattern recognition technology(SPRT) based on Mahalanobis distance theory(MDT) is not sufficient for monitoring structural conditions under largely variable external loads such as an earthquake. Structural damage is usually computed as a difference between the average measured value of undamaged structure and the average measured value of a damaged structure. So when the fluctuation of the load becomes larger the difference becomes larger and it can be easily mistaken as damage. This paper aims to overcome such problem and develops an improved Mahalanobis distance theory (IMDT), which is a SPRT based on revised MDT that decreases the effect of data variability, so that structure monitoring is possible even under unforeseen external loads. This method was experimentally tested to see if it could accurately measure the structural health of a cable-stayed bridge under both cyclic load and earthquake load. The results showed that the developed IMDT is valid for locating structural damage caused by damaged cables using the data obtained from undamaged cables. Finally the developed theory was proven to be effective for monitoring structural health of bridges under largely fluctuating external load.

.

New Statistical Pattern Recognition Technology for Condition Assessment of Cable-stayed Bridge under Earthquake Load

S. H. Lee[1] , G. H. Heo[2] and S. G. Seo[3]

ABSTRACT

In spite of its usefulness as a tool for monitoring health of structures under steady external load, the statistical pattern recognition technology (SPRT) based on Mahalanobis distance theory (MDT) is not sufficient for monitoring structural conditions –under largely variable external loads such as an earthquake. Structural damage is usually computed as a difference between the average measured value of undamaged structure and the average measured value of a damaged structure. So when the fluctuation of the load becomes larger the difference becomes larger and it can be easily mistaken as damage. This paper aims to overcome such problem and develops an improved Mahalanobis distance theory (IMDT), which is a SPRT based on revised MDT that decreases the effect of data variability, so that structure monitoring is possible even under unforeseen external loads. This method was experimentally tested to see if it could accurately measure the structural health of a cable-stayed bridge under both cyclic load and earthquake load. The results showed that the developed IMDT is valid for locating structural damage caused by damaged cables using the data obtained from undamaged cables. Finally the developed theory was proven to be effective for monitoring structural health of bridges under largely fluctuating external load.

Introduction

With advancements in construction technology and growths in social infrastructure, civilian structures such as docks, airports, tunnels, bridges, and buildings are becoming taller, wider, and larger in scale. But at the same time such structures are becoming more exposed to threats due to natural disasters such as hurricane and earthquake as well as to manmade risks such as too much load (going over maximum capacity and carrying extra loads) and terrorist attacks. Consequently researches are taking place to effectively monitor structural conditions and respond to threats in real time. Such assessment methods are called structural health monitoring (SHM)1). SHM monitors a current condition of structures based on a statistical analysis that looks for damage or warning signs from the structural responses measured by an array of sensors periodically monitoring the dynamics of the structure1). Such a health monitoring method is gaining more attention as it requires less manpower, no direct reaching for damaged spots, and no civilian distress such as traffic block that arise during direct damage assessments, compared to the conventional direct assessment methods such as naked eye assessment2). An outlier detection, one of the many different statistical development

---

[1] Professor in Civil and Environment Engineering at Pusan Nat'l University, South Korea (lsh77@pusan.ac.kr)

[2] Professor in Civil and Environment Engineering at Konyang Universiy, South Korea (heo@kyu.ac.kr)

[3] Professor in Civil and Environment Engineering at Chungnam Provincial Cheongyang College, South Korea (seo@cyc.ac.kr)

models, depends on a data mining technique that extracts new, hidden information by analyzing reciprocal relationships in between the data. Ruotolo and Surace$^{3)}$ used change of matrix rank for detecting outliers. Worden proposed a pattern recognition technique based on the transmissibility and Mahalanobis distance$^{4)}$. One of the well-known researches that utilize Mahalanobis distance theory was done by Nair and Kiremidjian$^{5)}$, and it proposes a method of assessing structural damage based on the Mahalanobis distance obtained from applying a vector in the Gaussian mixture model (GMM). The study was verified using simulation data from ASCE Benchmark Structure. Also Kiremidjian et al$^{5)}$ carried out a damage experiment on a three-span bridge under an earthquake load, and used the GMM-based Mahalanobis distance proposed in the previous study to classify damages. Kiremidjian et al$^{5)}$ verified the effectiveness of the GMM algorithm through small-scale experiments, but it still needs to be further verified with additional experiments. It also did not take into consideration the effect of local damage on the whole structure in complex structures. So this study looks at a Mahalanobis distance-based pattern recognition technique for detecting damages on a structurally complex cable-stayed bridge. It especially focuses on the effect of local damage on the structure as a whole that was not considered in previous studies.

Statistical Analysis Based on the Mahalanobis Distance

Normally the distance between two data points (x,y) are calculated as Euclidian distance as in equation (1) (O.R de Lautour$^{6)}$, .

$$D_E(x,y) = \sqrt{(x-y)^T (x-y)} \tag{1}$$

Such Euclidian distance is calculated by simply comparing the distance between two data points, and does not consider the variability of each data point. So, the data with higher variability need to be weighted with a standard deviation because without the weight the data itself can be mistaken for damage. Adding the weight of standard deviation to equation (1) gives equation (2).

$$D_E(u,v) = \sqrt{(x-y)^T R^{-1} (x-y)} \tag{2}$$

where $u = \left(\frac{x_1}{s_1},\ldots,\frac{x_n}{s_n}\right)$, $v = \left(\frac{y_1}{s_1},\ldots,\frac{y_n}{s_n}\right)$, s_i is standard deviation, $R = diag(s_1^2,\ldots,s_n^2)$ and a covariance matrix. If R is not a diagonal matrix the difference between the measured variables and the median values become the Mahalanobis distance, or MD. Such relationship can be expressed as in equation (3)

$$MD = \sqrt{(x-m)^T R^{-1} (x-m)} \tag{3}$$

where x is the measured value from the structure, m is the mean value of x, R is the covariance matrix of x. MD theory was first introduced for categorizing race mixtures in

1930⁶⁾. This theory is not merely a calculation of distance between two data points, but it is a calculation of distance while considering the standard deviation and relational coefficients of the particular variable

The MD of measured values such as x and y shows how larger the distance between the measured value and mean value are than the standard deviation. For example data with small fluctuations such as the cyclic load gives very large value of MD while data with large fluctuations such as the earthquake load gives very small value of MD. Therefore MD is not useful in detecting damage under earthquake load.

To improve such shortcomings this study proposes improved Mahalanobis distance (IMD) as in equation (4).

$$IMD = \sqrt{(\Delta x - m)^T R^{-1} (\Delta x - m)} \tag{4}$$

Δx in Equation (4) is the difference between x before damage and $\hat{x}$ after damage. Newly suggested IMD decreases the variability of largely fluctuating data to prevent drop in MD caused by largely fluctuating data.

A method is needed to assess structural health using the MD and IMD values. Therefore a control chart using the MD and IMD are defined in equation (5), (6), and (7).

$CL(\text{Center Line}) = \overline{MD}$ CL(Center Line) (5)

$UCL(\text{Upper Center Line}) = \overline{MD} + \alpha\sigma$ UCL(Upper Center Line) (6)

$LCL(\text{Lower Center Line}) = \overline{MD} - \alpha\sigma$ LCL(Lower Center Line) (7)

Here, $\overline{MD}$ is the mean value of Mahalanobis distance, α is the confidence interval of 99.7% in normal distributed curve, and σ is the standard deviation of the Mahalanobis. The MD and IMD calculated from measured data that go out of the range beyond defined upper center line and lower center line of the control chart indicate fault in structural health.

Structure Damage Experimental Test

Model Structure of Cable-stayed Bridge

For the experiment, a model of Seohae Grand Bridge, a cable-stayed bridge, reduced 200 to 1 in scale, was built and used. The two-pylon bridge model of 4.2 meters in length, 0.7 meters in maximum height, and 2.24 meters in middle span length was installed in the structural experiment room of the department of civil and environment engineering at Konyang University in Korea. In order to generate maximum vertical displacement of the center span, the abutment where the shaker is installed supports the deck using a hinge while other three abutments support the deck using a roller. Also to deliver the external load from the shaker to the bridge, two lateral reinforcements, 0.03 m in width and 4.22 m in length and a square shaped crossbeam 0.17 m in length, are attached. This crossbeam acts as a connection to the cable and to the extra load (1 kg). The cable-stayed bridge model described is as shown in figure 1.

Figure 1. Cable-stayed bridge model

The cable tension of the bridge model was determined by means of the cable tension analysis program SAP2000. The fixed load condition considers the total weight of both two lateral reinforcements and the extra load. The cable tension (Newton, N) calculated via the program is displayed in figure 2, and each cable tension of the structure in figure 1 was tuned using the calculated values.

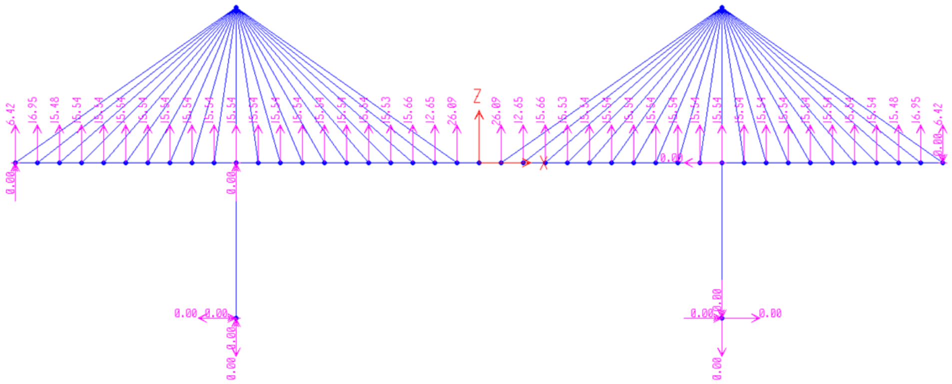


Figure 2. Calculation of cable tensions

Configuration and Installation of the Experimental Instrument

In order to acquire damage data of the target structure, the experiment instruments are divided into two, an external load placing system that induces the damage and a measurement system that acquires structural response data. The system is controlled using the unified wireless control (UWC) system using cRIO-9014 and cRIO-9104 of National Instruments (G. Heo, C. Kim, 2012). First, for the external load inducing system, an electronic shaker set (EDS20-120 and Power Amplifier 1200) is installed as in figure 3 and it is controlled by the UWC system. The sensors that measure structural acceleration and tension are 3055B3 of Dytran and CDFS-10 load cell of Bongshin. The external load inducing system and the measurement system are installed on the structure as seen in figure 3.

The structural vibration is induced by electronic shaker that puts load in vertical directions from the center of the left span of the bridge as seen in figure 3. The structural responses in vertical direction are measured from accelerometers installed in the center of each bridge span while each cable tension is obtained from load cells installed on the cables one and two, left of the bridge center.

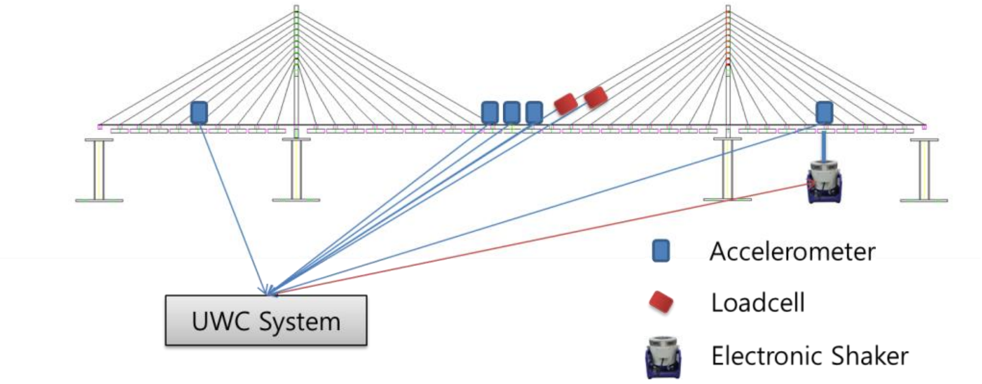


Figure 3. Arrangement of test devices

Acquiring Damage Data

In order to evaluate the structural health using the statistical pattern recognition tool MDT, MD and control chart based on MD calculation need to be obtained during the normal state of the structure in advance. The MD of undamaged structure can be then compared to the MD of damaged structure. For these purposes, an experiment was carried out to obtain the data of damage under cyclic load and earthquake load, and the cables are numbered as in figure 4.

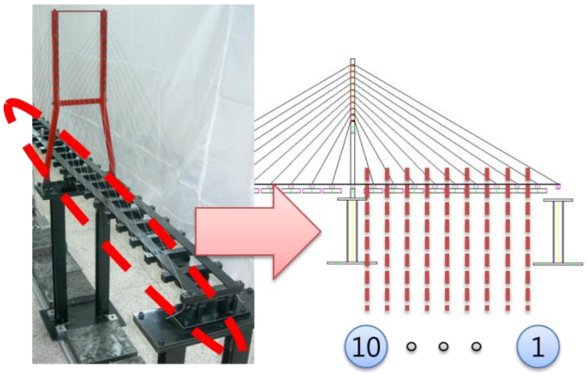


Figure 4. Cable numbers

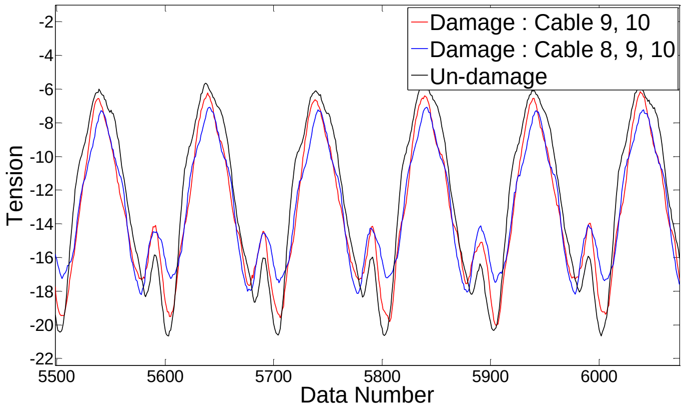
The cyclic load experiment was carried out by shaking the structure for 10 seconds with 20 Hz sine wave for 80 reps. Next, the earthquake load experiment was carried out by shaking the structure with E1 Centro wave for 40 reps. The end of each load was marked by the damages starting to occur in the six cables that face in the same direction of the load cells. The MD is then calculated using data of both undamaged and damaged cables, and the control chart is accordingly to the calculated MD.

Experiment Results and Evaluation of Statistical Pattern Recognition

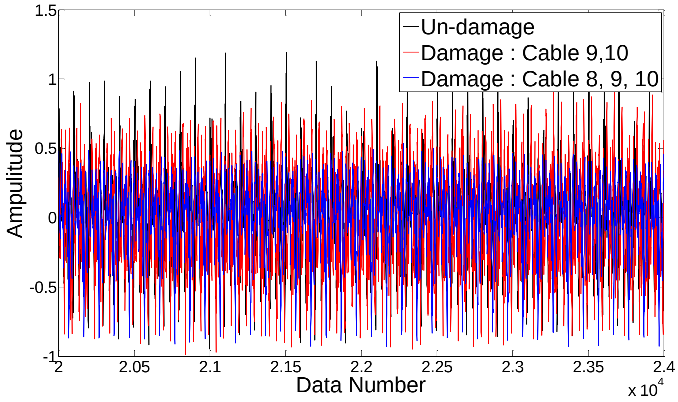
Experimental Results

Structural responses were obtained under cyclic load and earthquake load in order to assess the condition of cable-stayed structure using the statistical pattern recognition technique.

First, acceleration response and cable tension response to the cyclic load shaking the structure at 20 Hz are plotted as seen in figure 5.



(a) Cable tensions

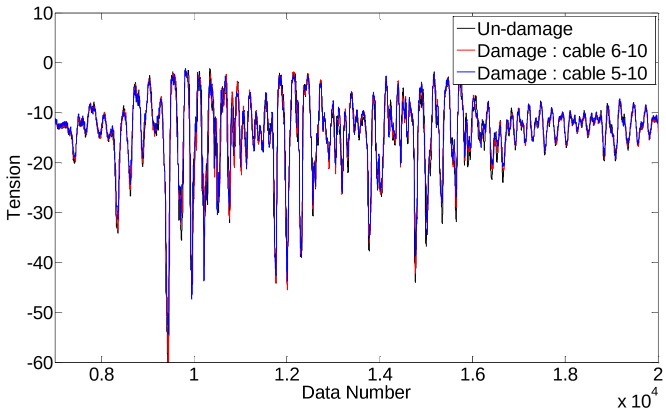


(b) Acceleration of the center span

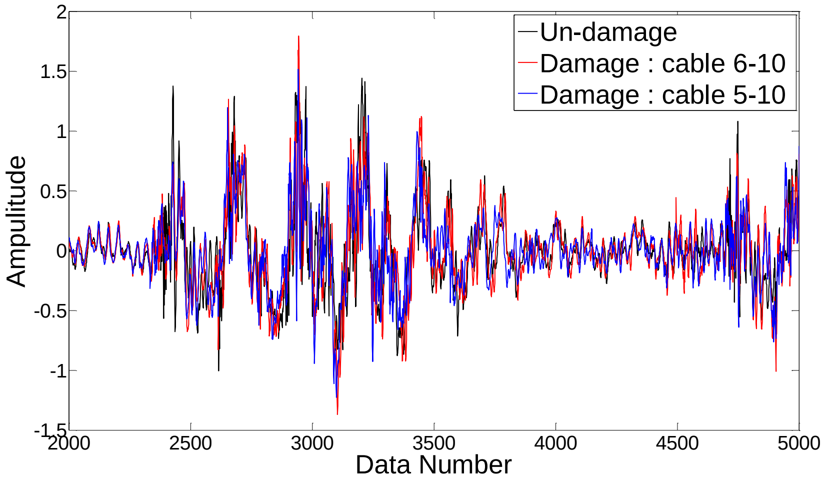
Figure 5. Structural response under the cyclic load

Figure 5 plots the cases where none of the cables are damaged, two of the cables are damaged, and three of the cables are damaged. As figure 5(a) shows, there are some differences in cable tension due to the differences in the cable damage, but there are no notable differences in the acceleration responses due to the cable damage as in figure 5(b).

Next, figure 6 plots cable tension and acceleration responses of the structure under the E1-centro earthquake load.



(a) Cable tension



(b) Acceleration of the center span

Figure 6. Structural response under the earthquake load

Figure 6 plots the responses where the cables are not damaged, four of the cables are damaged, and five of the cables are damaged. As figure 6(a) and (b) show, the cable tension and acceleration response show no notable difference against the cable damage.

Structural Health Assessment Using the Control Chart

As it was demonstrated by the experiment results in 4.1, there is no notable difference in the cable tension and the acceleration responses of center span due to the damage in cable. Now we will assess the structural health using the MDT and IMDT values since the obtained experimental data alone cannot perform such an assessment. First, MD is computed based on the data obtained under the cyclic load, and the control chart is configured accordingly as in figure 7.

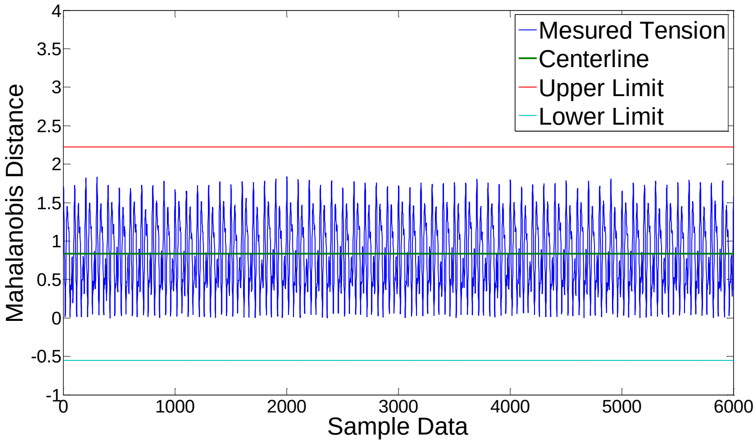


Figure 7. Control chart (using MDT)

Figure 7 computes the MD using equation (3) and the undamaged cable tension values under the cyclic load. Using these calculations and equation (5)~(7), the centerline, upper limit, and lower limit of the chart are determined. Based on the determined control chart in figure 7, the structural health can be evaluated using the MD calculated from the obtained data of damaged cables. Figure 8 is the control chart of damaged cables under the cyclic load.

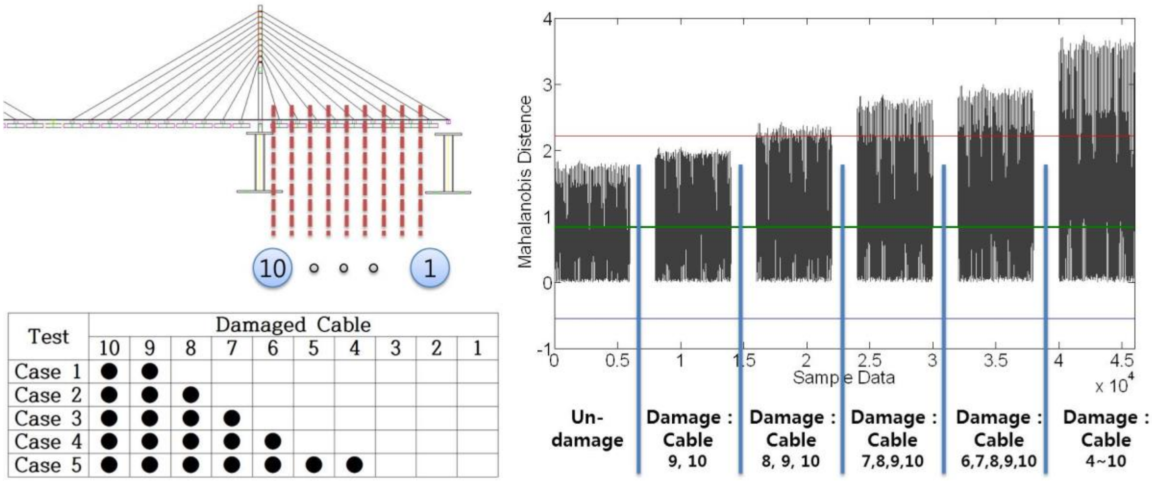


Figure 8. Performance evaluation of control chart under repeated load

Figure 8 classifies the condition of the structure into five sections by its level of cable damage based on the control chart. As figure 8 demonstrates, the MD of control chart using the MDT increases with the increased number of damaged cables, and it goes above the upper limit of the control chart when more than three cables are damaged. In other words, an immediate action needs to be taken when more than three cables are damaged.

Similar to figure 7 and 8, a control chart was formed to assess the structural health of the bridge under the earthquake load, and the condition of the structure was assessed using damaged cables. Figure 9 is a control chart based on the MD of structural health under the earthquake load.

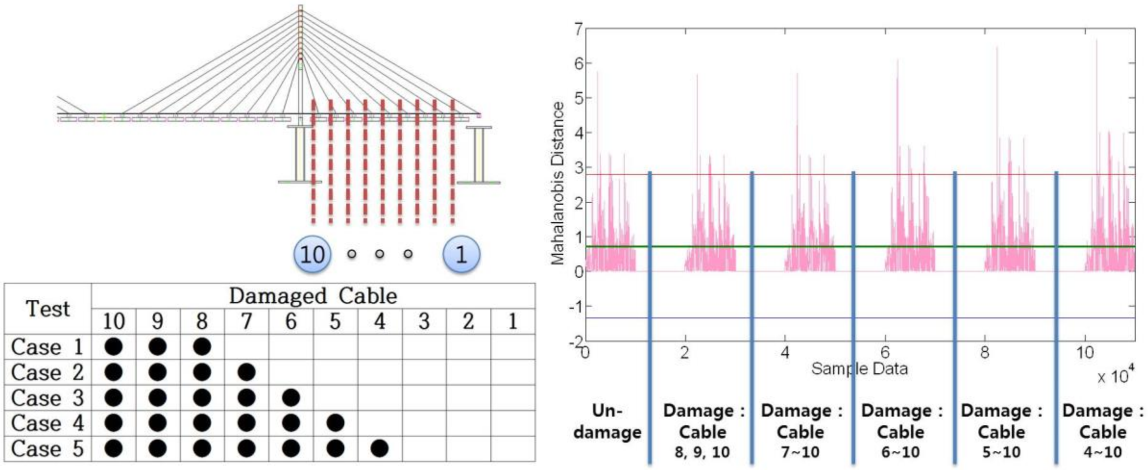


Figure 9. Performance evaluation of control charts under the earthquake load

The control chart in figure 9 classifies cable damages into five sections based on the control chart of undamaged cables, and evaluates the condition of the structure. As seen in figure 9, a control chart using MDT under the earthquake load is not accurate because it has large fluctuations in the data even when cables are undamaged. Therefore, the MD based on damaged cables is not notably different from the MD based on undamaged cables. Therefore, the original MDT is not suitable for assessing the condition of structure undergoing largely fluctuating impact such as earthquake.

So the condition of the structure is assessed using the proposed IMDT. The assessment procedure is similar to the previous MD based control chart and the assessment of structural health by cable damage. The difference is that the equation (4) is used for calculating IMD, and the structural health by cable damage is evaluated based on the calculated IMD as in figure 10 and table 1.

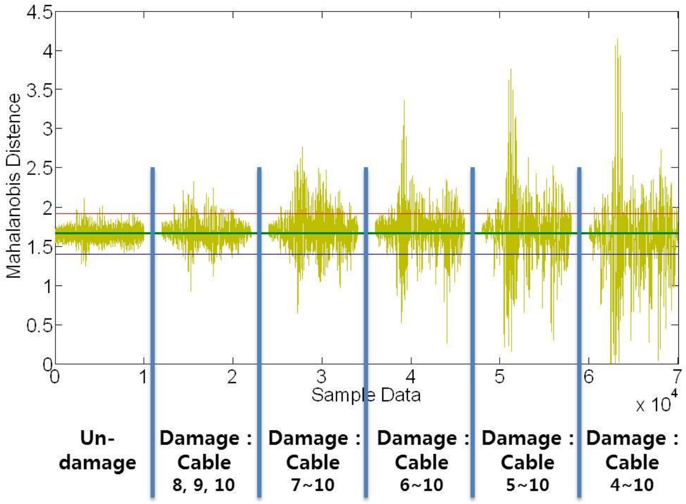


Figure 10. Performance Evaluation of Control Charts (using IMDT)

Table 1. Comparison of RMS value

Damaged cable	RMS	None	Damage rate (%)
None	0.0857	1	-
8,9,10	0.1329	1.55	35.48
7-10	0.2254	2.63	61.98
6-10	0.2556	2.98	66.44
5-10	0.3671	4.28	76.63
4-10	0.4597	5.36	81.34

The control chart in figure 10 is formulated using the IMDT when no cables are damaged, and the structural health is evaluated by computing the IMD as cables become damaged. The IMDT based control chart in figure 10 shows that with the increasing number of damaged cables, the IMD goes to extremes with increasing magnitude. Also with the increasing number of damaged cables, the RMS value increases compared to the RMS of undamaged cables as seen in table 1. It can be seen that the amount of damage becomes greater when the cables near the center of each span are damaged. Conclusively the proposed IMDT can accurately capture structural health even under largely fluctuating earthquake load.

Conclusion

This study uses a statistical pattern recognition technology in order to assess structural health of complex structures such as a cable-stayed bridge. The statistical pattern recognition technology applied in this study is not merely a distance calculation between two data points, but a control chart based on Mahalanobis distance theory that considers the standard deviation and relational coefficients in order to capture the effect of variability of the data. The conclusions are as follows:

1) The control chart based on Mahalanobis distance theory is an appropriate statistical pattern recognition tool for evaluating the health condition of a structure under small fluctuating load such as the cyclic load and small external load. However, it was experimentally proven to be not adequate for assessing the structural health under largely fluctuating loads such as an earthquake.
2) The improved Mahalanobis distance theory was designed to overcome the limits of the original Mahalanobis distance theory, and it was superior in assessing the structural health under largely fluctuating earthquake load.
3) The improved Mahalanobis distance theory was validated as a statistical pattern recognition tool because it was able to use just the cable data from the center span and not the data of damaged cables in the side spans to assess the structural health during the experiments on the effect of local damage on the whole structure.

Acknowledgments

This research was supported by National Research Foundation of Korea through funding from the Ministry of Education (Project No: NRF-2013R1A2A1A01016192, NRF-2010-0024250 and NRF-2011-0023229, NRF-2013R1A1A2059914). Many appreciation and acknowledgements go to the National Research Foundation who made this research possible.

References

1. Charles R. Farrar and Hoon Sohn. (2000) “Pattern Recognition for Structural Health Monitoring. ” *Workshop on Mitigation of Earthquake Disaster by Advanced Technologies,* Las Vegas, NV, USA, LA-UR-00-5565.
2. Wang Z. and Ong KCG. (2009) “Structural damage detection using autoregressive-model-incorporating multivariate exponentially weighted moving average control chart.” *Eng Struct*, Vol 31(5), pp. 1265–1275.
3. Ruotolo, R., and Surace, C. (1997) “Damage Detection Using Singular Value Decomposition.” *Structural Damage Assessment Using Advanced Signal Processing Procedures*, Proceedings of DAMAS ‘97, University of Sheffield, UK, pp. 87–96.
4. K. Worden, G. Manson, and N. R. J. (2000) “Damage detection using outlier analysis.” *Journal of Sound and Vibration*, Vol. 229(3), pp. 647-667.
5. Anne S. Kiremidjian, Garo Kiremidjian and Pooya Sarabandi. (2011) “A Wireless Structural Monitoring System with Embedded Damage Algorithms and Decision Support System.” *Structure and Infrastructure Engineering*, Vol. 7, No. 12, pp. 881–894.
6. P C Mahalanobis. (1930) “On tests and measures of group divergence.” *Journal of the Asiatic Society of Bengal*, Vol. 26, pp. 541–588.