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A STRUCTURAL HEALTH MONITORING SYSTEM FOR A DAMAGED CLASSROOM BUILDING DISPLAYED IN THE 921 EARTHQUAKE MUSEUM OF TAIWAN

J. F. Wang[1] and C. C. Lin[2]

ABSTRACT

This paper presents a study on the development of structural health monitoring (SHM) system for evaluating the safety of a damaged classroom building displayed at the 921 Earthquake Museum of Taiwan (921EMT). The monitored structure is a one-story building that was previously a classroom in Kuang-Fu Middle School. It was severely damaged in the Taiwan Chi-Chi earthquake on September 21, 1999. The classroom was subsequently strengthened with acrylic glass walls and has been on display at the 921EMT since 2007. Because visitors are permitted to walk inside the building, a long-term SHM system was developed to provide safety warnings for this building. A hardware system including a sensor array and a central data recording and processing module was firstly installed at the end of 2010. Seismic responses of this structure were collected and a system identification technique was employed to extract its dynamic properties as structural health baselines. A structural health diagnosis procedure was established and has been coded as software and tested using later earthquake events. The results of this study could provide a reliable SHM strategy for the displayed damage building.

[1]Assistant Research Fellow, 921 Earthquake Museum of Taiwan, National Museum of Natural Science, Taichung City, Taiwan 413, R.O.C.
[2]Distinguished Professor, Dept. of Civil Engineering, National Chung Hsing University, Taichung City, Taiwan 412, R.O.C.

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ABSTRACT

This paper presents a study on the development of structural health monitoring (SHM) system for evaluating the safety of a damaged classroom building displayed at the 921 Earthquake Museum of Taiwan (921EMT). The monitored structure is a one-story building that was previously a classroom in Kuang-Fu Middle School. It was severely damaged in the Taiwan Chi-Chi earthquake on September 21, 1999. The classroom was subsequently strengthened with acrylic glass walls and has been on display at the 921EMT since 2007. Because visitors are permitted to walk inside the building, a long-term SHM system was developed to provide safety warnings for this building. A hardware system including a sensor array and a central data recording and processing module was firstly installed at the end of 2010. Seismic responses of this structure were collected and a system identification technique was employed to extract its dynamic properties as structural health baselines. A structural health diagnosis procedure was established and has been coded as software and tested using later earthquake events. The results of this study could provide a reliable SHM strategy for the displayed damage building.

Introduction

On 21st of September, 1999, the Chi-Chi earthquake with 7.6 on the moment magnitude scale took place on the Taiwan Island, resulted in damages of field track and classroom buildings at the Kuangfu Middle School in Wufeng Village, Taichung County (present Wufeng Dist., Taichung City). To preserve this site for commemoration and education, an earthquake museum, named “921 Earthquake Museum of Taiwan (921EMT)”, was built and has been opening to the public since 2004. The “Damaged South Classroom (DSC)” is one of the preserved buildings which provides visitors an opportunity to observe building damage in detail. To strengthen this building for public safety and display, acrylic-glass walls (AWs) are used to reduce the interference from added components. However, acrylic material has rarely been used for structural members in buildings. Its long-term reliability is unclear in real building cases. To monitor the health condition of the DSC building, a structural health monitoring system has been deployed since 2010. The purpose of this study is to introduce the instrumented system and to develop a SHM strategy for the DSC building. This study began with the collection of seismic response measurements. The system identification (SID) technique, named System Realization Using Information Matrix (SRIM) [1-3], was employed to obtain the modal parameters of the

[1] Assistant Research Fellow, 921 Earthquake Museum of Taiwan, National Museum of Natural Science, Taichung City, Taiwan 413, R.O.C.
[2] Distinguished Professor, Dept. of Civil Engineering, National Chung Hsing University, Taichung City, Taiwan 412, R.O.C.

DSC building as structural health baselines based on acceleration measurements from 30 earthquake events. To establish stable baselines, a signal-processing procedure with tail extraction and high-frequency filtering was performed before the SID. It is expected that the outcome of this study can be applied in the safety management for the DSC building.

Overview of the SHM System of the Damaged School Building

There are three damaged classroom buildings preserved for exhibitions in 921EMT,. Two of them received serious damage (totally collapsed in some portions or stories) due to the passage of the Chelungpu fault line. Museum visitors are not permitted to approach them for safety concern. The third damaged building is the South Damaged Classroom (DSC) which is a couple of meters away from the fault line. The ground floor of the DSC building is basically intact, whereas all the columns are laterally displaced and cracked. The outer concrete of some columns is chipped off and the interior reinforcements are exposed. These damage features are regarded as live education materials. Therefore, the DSC building has been strengthened to provide its structural safety.

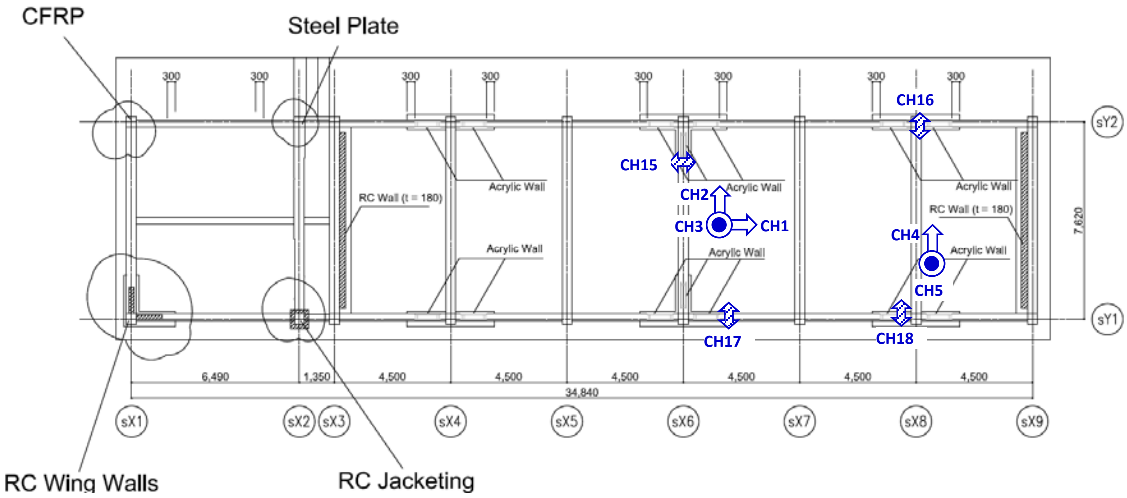
Building description

The original DSC building is located at the footwall of the Chelungpu fault and only meters distant from the fault line. It received serious column damage along the corridor (x-direction) during the 1999 Chi-Chi Earthquake. The exhibition structure is a one-story building with 35m × 11m base plan. In design, the exhibition structure is demanded to be capable of resisting gravity and earthquake loadings. Besides, the newly added components were demanded not to affect the display of the original damage appearance. Therefore, fourteen acrylic-glass walls were installed beside the damaged columns as the vertical and horizontal resisting elements, as shown in Fig. 1.

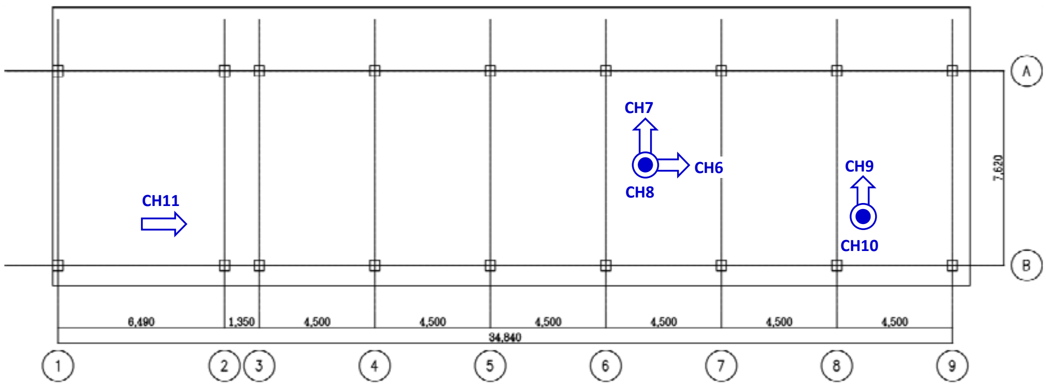
Figure 1. The Damaged South Classroom in 921 Earthquake Museum of Taiwan (Left: View from northwest; Right: AW retrofit)

Sensor array

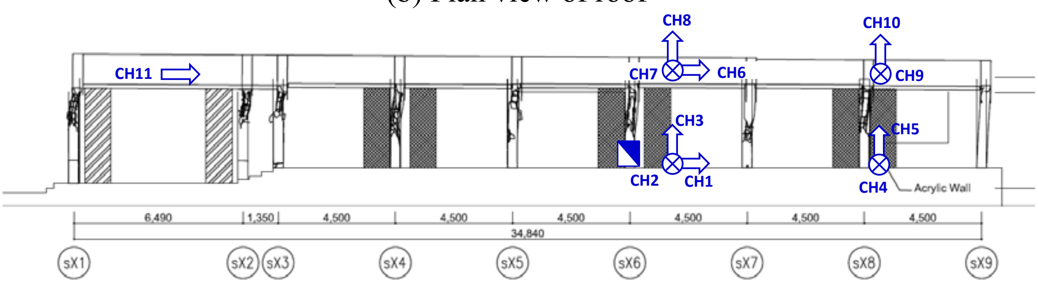
The instrument of a sensor array for the DSC building was completed in December of 2010. There are 15 sensors installed. Five uni-axial accelerometers are instrumented at two locations of the ground floor. Five uni-axial velocity sensors and one accelerometer are instrumented at three locations of the roof. Four displacement sensors are installed at four different AWs, respectively. Fig. 2 presents the location, measured direction, and channel label of each sensor. Fig. 3 shows the pictures of the three sensor types.



(a) Plan view of fist floor



(b) Plan view of roof



(c) Elevation view from south

Figure 2. Sensor array layout (⇨: the arrow directs to the positive; ⊙: the positive direction points out from the paper; ⊗: the positive direction points in to the paper; ⇔: displacement transducer measured axis)

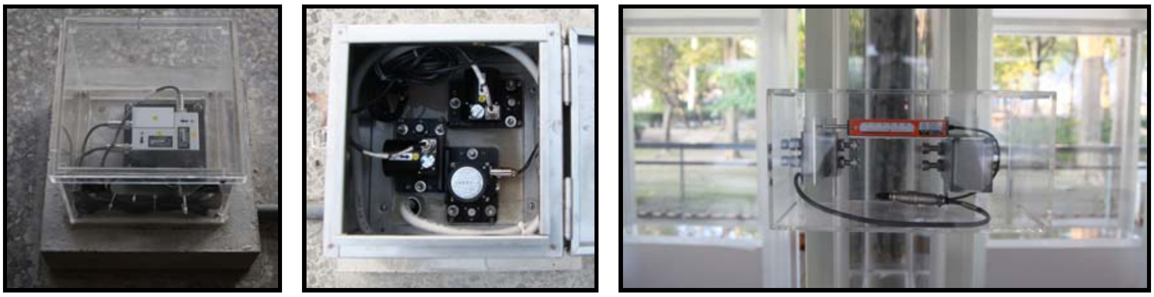


Figure 3. Left: CH1, CH2, and CH3 accelerometers; Middle: CH6, CH7, and CH8 velocity sensors; Right: displacement transducer

Dynamic Parameter Identification

I/O Setup

Acceleration measurements from thirty earthquake events were collected. The largest event is a 6.3-magnitude event took place on 2010/11/21 near Hualien. To understand the dynamic parameters of the DSC building under seismically-excited ground motions, the SRIM MIMO identification technique was employed. CH1, CH2, and CH3 (the ground accelerations in x-, y-, and z-directions, respectively) were regarded as the input and CH6 to CH11 (on the roof) were considered as the output. The modal parameters of the first four modes from all the events were identified.

Mode shape

Tables 1 and 2 present the mode shapes identified from 2010/11/21(M_L=6.1) and 2011/02/08 (M_L=3.6) earthquake events. These results show that the CH6 (x) and CH11(x) components dominate the first mode shape and the rest components are smaller than 8% of the dominant component. This means that the first mode shape of the DSC building is approximately the x-direction rigid-body motion of the roof. The second to the fourth mode shapes are mainly dominated by vertical motion of the roof with different degrees of coupling with x- and y-directions. Different proportions between CH08 (z) and CH10 (z) components indicate that these higher modes could be out-of-plan deformation of the roof floor. There are no y-direction dominated modes, which imply that the y-direction of the DSC building is stiffer than in the other two directions. These results show that the weakness of the DSC building is along the x-direction.

Modal frequency

The modal frequencies of the first four modes based on measurements from thirty earthquake events were also identified. Table 1 shows that larger ground acceleration may decrease the modal frequency of the DSC building. Fig. 4 plots the modal frequencies of the first four modes versus the peak ground acceleration in x- or z-direction, where a circle symbol represents an event. The solid curves and equations represent the result of statistical curve fitting to the 30 samples, and two dash curves indicate the ±5% variation ranges. The use of PGA_x or PGA_z depends on the dominated direction of each mode. It is seen that each modal frequency had a decreasing with the increasing of PGA, in particular the first modal frequency. The variation percentages from the fitting curves of almost all of the data points are smaller than 5%.

Table 1. Modal frequency and mode shape from the 2010/11/21 Hualien Earthquake event

(a)first-half measurement

	Mode	1	2	3	4
	Modal frequency(Hz)	7.4	11.3	15.2	19.6
Mode shape	CH06(x)	1.000	-0.021	-0.052	0.151
	CH07(y)	-0.026	-0.056	-0.246	-0.084
	CH08(z)	0.080	-0.175	-1.000	1.000
	CH09(y)	-0.038	0.177	-0.250	-0.115
	CH10(z)	-0.011	1.000	-0.068	0.341
	CH11(x)	0.912	-0.019	-0.070	-0.017

(b)second-half measurement (strong-motion part)

	Mode	1	2	3	4
	Modal frequency(Hz)	6.69	11.2	14.7	19.4
Mode shape	CH06(x)	1.000	-0.027	-0.046	0.205
	CH07(y)	-0.028	-0.069	0.216	-0.327
	CH08(z)	-0.027	-0.356	-1.000	1.000
	CH09(y)	-0.072	0.177	-0.206	-0.190
	CH10(z)	-0.057	1.000	-0.059	0.345
	CH11(x)	0.951	-0.016	-0.061	-0.130

Table 2. Modal frequency and mode shape from the 2011/02/08 Taichung Earthquake event

	Mode	1	2	3	4
	Modal frequency(Hz)	7.53	11.6	14.9	20.1
Mode shape	CH06(x)	1.000	0.013	0.042	0.122
	CH07(y)	-0.033	-0.167	-0.240	-0.135
	CH08(z)	-0.021	-0.540	-1.000	1.000
	CH09(y)	-0.068	0.118	-0.176	-0.045
	CH10(z)	-0.082	1.000	-0.064	0.492
	CH11(x)	0.900	-0.024	-0.033	-0.042

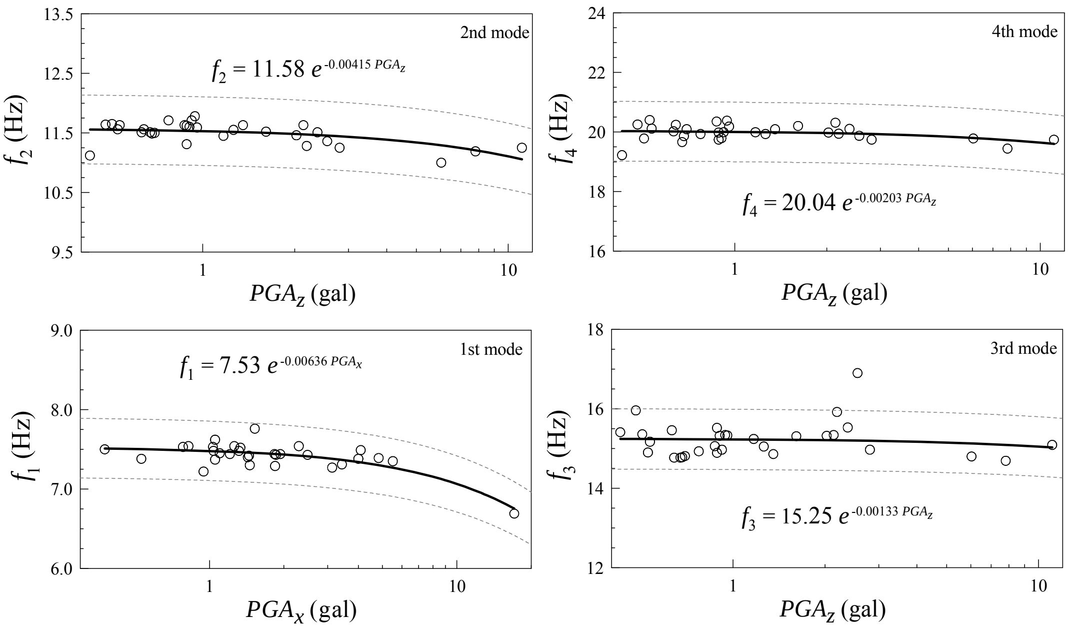


Figure 4. Identified modal frequencies of the DSC building versus peak ground acceleration

Modal damping

Table 3 presents the mean and range of the identified modal damping ratio of the first four modes. It can be seen that the variations are much larger than those for modal frequency. The maximum modal damping ratio (6.24%) is from the strong-motion part of the 2010/11/21 Hualien Earthquake. It may imply that the damping effect of the DSC building can be amplified with the increase of deformation. In average, the modal damping ratio seems as small as that of a steel structure.

Table 3. Mean and range of identified modal damping ratio of the DSC building

Mode	1	2	3	4
Mean (%)	1.53	1.73	2.88	0.83
Range (%)	0.4~6.24	1.17~2.77	1.46~4.8	0.33~1.68

Structural Health Baselines of the DSC building

Signal tail extraction

Results from the above section show that the modal frequencies of the DSC building may temporarily decrease with the increase of PGA. This frequency decreasing phenomenon could result from geometry nonlinearity that is not related to structural damage. Although statistical expressions for modal frequencies in terms of PGA were established, most of the samples are of small PGAs. There are potential uncertainties with larger PGAs. To solve this problem, we retrieved the measurement signals from the end to the beginning and stopped retrieving at a threshold of 2 gal and sent them to the SID procedure. By doing this, the uncertainties in dealing with larger PGA signals could be reduced.

SRIM parameter setup

To employ the SRIM technique, four parameters need to be set by users: *n*, *k*, *p*, and *N*, as shown in Fig.5. The setup in this study is stated below:

Parameter *n*:
Parameter *n* represents the order of the system. Generally, it is set to be an even integer. In theory, *n* is equivalent to the number of non-zero singular value of a specific matrix. However, it could be a difficult task in real case. In this study, different *n* was used and we determined to set *n*=4 where best identification results were drawn in this building case.

Parameters *k*, *p*, and *N*:
Parameter *k* represents the first point of the signal to be used in SRIM procedure. Because the signals have already been truncated, $k = 1$ was set in the following study. In theory, $1 < N < (N_t + k + 1)$ and $1 < p < (N_t + N - k + 2)$, where N_t is the total number of points of a signal segment. In other words, there are $(N_t + k + 1) \times (N_t + N - k + 2)$ sets of (p, N). Although we could search for the best identification result by going through all the (p, N) sets, this would

be time-consuming and a desktop PC could not have enough hardware resource. In this study, we considered a proper range of (p, N) and started with larger intervals for p and N. A finer interval was set when an outlier was found to make confirmation.

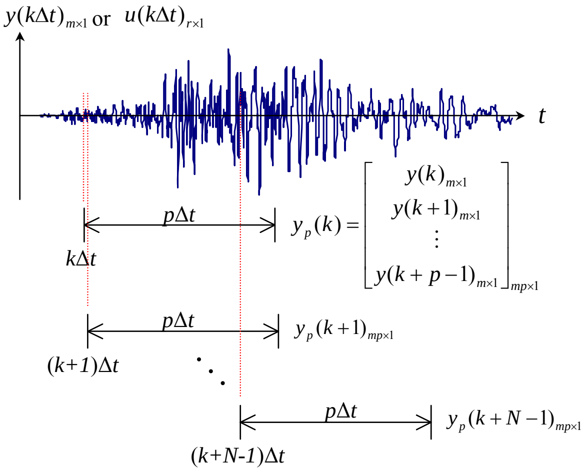


Figure 5. Construction of the input and output information matrices in SRIM technique

Criteria for optimum identification results

The following steps were used in this study to determine the optimum identification result for a single event:

Step 1:

For each identified system from a specific (p, N) set, the building acceleration response, $y'(t)$, was reconstructed using the known ground acceleration. Let $y(t)$ be the real acceleration measurement of the building. The least-square error, J, between $y(t)$ and $y'(t)$ of each identification set was calculated. Place all the result sets in ascending order of J. Choose the first set as the optimum result (with minimum J).

Step 2:

Collect all the optimum modal frequencies from each seismic event. Calculate the mean of modal frequency of each mode from the 30 earthquake events.

Step 3:

Compare the optimum modal frequencies from each event with the mean value in step 2. If the difference is larger than 20%, replace the current optimum identified system with the next one. Repeat the comparison until the difference is smaller than 20%. This step is to ensure the optimum identified system from a single event follows the trend of the group of the 30 samples.

Step 4:

Check if the damping ratio (ξ) of the current optimum identified system is reasonable, that is, $0 < \xi < 1$. If not, choose the next set as the optimum identified system and repeat step 3 to step 4. If yes, the current identified set is the optimum set.

Fig. 6 shows the optimum set of the first modal frequency, modal damping ratio, and mode shape ratio (CH6 component/CH11 component) from the 30 earthquake events. It can be shown that the variation of the first modal frequency is limited to 3% of the mean value, 7.42Hz, except that of the 8th event. In addition, the mode shape ratio is also limited to ±3% of 1.098. The variation of damping ratio is larger than the others, which means it is not suitable to be a baseline of the DSC building.

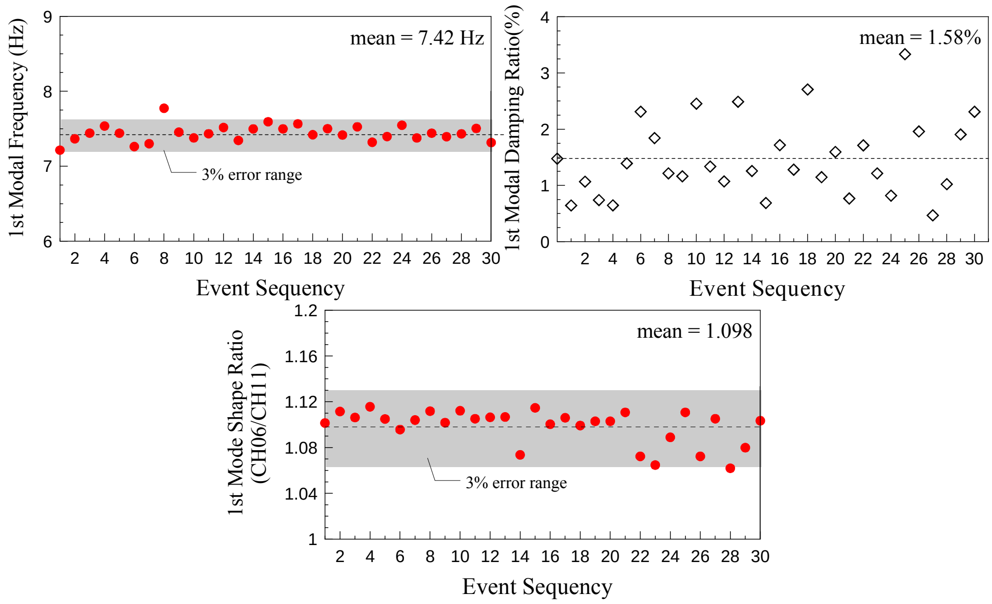


Figure 6. Optimum identified results of 1st modal frequency, 1st modal damping ratio, and 1st mode shape ratio (CH6/CH11) via the proposed criterion

Structural Health Diagnosis Procedure for the DSC Building

From the study mentioned above, it is shown that the fundamental mode shape of the DSC building is mainly the translation of roof floor along the corridor (x) direction. In addition, there is no apparent x or y component in the second, third, and fourth mode shapes. Hence, the structural health diagnosis procedure is proposed as follows:

1. After the shake of an earthquake, perform SRIM SID with truncated signals (threshold = 2 gal; n = 8). Search for the optimum identification set with a proper range and larger intervals for p and N. This is to obtain the modal parameters of the DSC building as soon as possible. If the identified first modal frequency is within the range of 7.42Hz±0.22Hz, give it a green (safe) light.
2. Repeat step 1, but search with smaller intervals for p and N. This is to ensure the result in step 1 is correct.
3. If the first modal frequency has 3% reduction (≦ 7.20Hz), the building could be damaged. Give a yellow light and set a warning alarm. If the reduction is larger than 5% (≦ 7.02Hz),

give a red light and set a damage alarm. It is suggested to temporarily close the normal visitor trail in the DSC building.

4. Detect if irregular damage occurs by observing the first mode shape ratio (CH6/CH11). If the first mode shape ratio is out of the range of 1.098±0.033, it could be an indication of irregular damage. This can be checked by observing the first mode shape ratio of the CH7 component to the CH9 component (y-direction). This study showed that the ratio is within the range of 0.015 to 0.065 in health state.

Conclusions

In this study, a structural health diagnosis procedure is proposed for the DSC building in the 921 Earthquake Museum of Taiwan. In view of dynamic behavior, the DSC building is prone to have translation along the corridor (x) direction with the frequency of 7.42 Hz in average. The y-direction translation is much smaller than that of the x-direction. This trend is same as the original DSC building before it was damaged. In addition, this study develops a procedure to determine stable structural health baselines with the employment of the SRIM technique. The obtained first modal frequency in health state is 7.42Hz±0.22Hz and the first modal shape ratio of CH6/CH11 is 1.098±0.033. Both are limited to variation of 3%. These can be used to detect the occurrence of damage for the DSC building and check if irregular damage occurs, which can be helpful for the safety decision of visitor management in the museum.

Acknowledgments

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References

1. Juang, J.N. System Realization using Information Matrix. *Journal of Guidance, Control, and Dynamics* 1997; **21**(3): 492-500.

2. Lin, C.C., Wang, C.E., Wu, H.W., Wang, J.F. On-line building damage assessment based on earthquake records. *Smart Materials and Structures* 2005;**14**(3): S137-S153.

3. Lin, C.C., Wang, J.F., Tsai, C.H. Dynamic parameter identifications for irregular buildings considering soil-structure interaction effects. *Earthquake Spectra* 2009; **24**(3): 641-666.

4. International Code Council, *International Building Code* 2009; USA.