POST-EARTHQUAKE DAMAGE IDENTIFICATION OF TALL BUILDING STRUCTURES: EXPERIMENTAL VERIFICATION

W.Y. Liao[1], W.H. Chen[2], Y.Q. Ni[3] and J.M. Ko[4]

[1] *PhD Candidate, Dept. of Civil & Structural Engineering, Hong Kong Polytechnic University, Hong Kong*
[2] *Research Assistant, Dept. of Civil & Structural Engineering, Hong Kong Polytechnic University, Hong Kong*
[3] *Associate Professor, Dept. of Civil & Structural Engineering, Hong Kong Polytechnic University, Hong Kong*
[4] *Chair Professor, Dept. of Civil & Structural Engineering, Hong Kong Polytechnic University, Hong Kong*
Email:weiyang.liao@polyu.edu.hk, cewhchen@polyu.edu.hk, ceyqni@polyu.edu.hk, cejmko@polyu.edu.hk

ABSTRACT :

While a variety of modal-based damage indices have been proposed in the past two decades, their applicability to seismic damage detection of building structures has scarcely been verified using real measurement data. This paper presents an experimental verification study on vibration-based post-earthquake damage identification of tall building structures. A 1:20 scale model of a 38-story residential building was tested on a shaking table to subject to four levels of earthquake (minor, moderate, strong, and super-strong earthquakes). Accordingly, the structure suffered from trifling, moderate, serious, and complete (nearly collapsed) damage, respectively. After the earthquake excitations at each level, post-earthquake ambient vibration responses of the tested structure were measured by accelerometers deployed at different floors. This experiment makes it possible to verify the applicability of vibration-based identification methods in identifying damage of different severities for the same structure. With the identified modal properties from ambient vibration responses, damage in the structure after experiencing each level of the earthquake attacks is evaluated making use of five modal-based damage indices, respectively. By comparing the identification and observation results, it is concluded that the modal flexibility damage index (MFDI), story damage index (SDI), and approximate story damage index (ASDI) perform well in identifying and localizing the seismic damage of different severities.

KEYWORDS: Tall buildings, seismic damage, vibration-based identification, experiments

1. INTRODUCTION

The devastating Wenchuan Earthquake occurring in southwest China's Sichuan Province on 12 May 2008 has highlighted again the need for real time damage assessment of important and critical civil structures after a major hazardous even. Knowledge of structural damage is the basis for decision making on whether retrofitting, partial replacement or demolition is necessary after severe hazards. Despite much recent research and some successful applications in recent years, assessing post-earthquake damage that occurs in complex structures such as tall building structures remains as a challenging task for civil engineers. Since the ambient vibration responses of a tall building structure before and after experiencing an earthquake can be easily measured, the vibration-based damage detection technique has attracted great interest for researchers and engineers in the past two decades (Ko and Ni 1999). Utilizing the ambient vibration monitoring data prior to and posterior to an earthquake in conjunction with an appropriate vibration-based identification method offers a viable approach to post-earthquake damage evaluation of tall buildings.

A variety of modal-based damage indices have been proposed for structural damage identification (Sohn et al. 2004). However, their applicability to tall building structures for post-earthquake damage identification has scarcely been verified using real measurement data. In particular, no experimental study has been carried out on examining and comparing their performance in identifying different levels of damage. In the present study, an experimental verification is conducted on a 38-story tall building model to compare the damage identification capability of various modal-based indices when the structure suffers from different levels of seismic damage. This 1:20 scale reinforced concrete structure represents a typical high-rise apartment building in Hong Kong with large open-space at the lower stories. It is tested on a shaking table to subject to four levels of earthquake including minor earthquake, moderate earthquake, strong earthquake and super-strong earthquake. Accordingly, the structure suffers from trifling, moderate, serious and complete (nearly collapsed) damage, respectively. After exerting earthquake excitation at each level, white-noise random excitation is applied to the structure to imitate ambient vibration, and the acceleration responses at nine floors of the structure during the ambient vibration are measured. Natural frequencies and mode shapes of the tested structure in healthy state and after incurring each of the damage scenarios are identified from output-only response signals and used to construct five damage indices which are the coordinate modal assurance criterion (COMAC), mode shape based *Z*-value, modal flexibility damage index (MFDI), story damage index (SDI), and approximate story damage index (ASDI). All these indices can be obtained without use of a structural finite element model. The performance of these indices in identifying trifling, moderate and serious damage is evaluated by comparing the predicted damage with true damage observed during the tests.

2. EXPERIMETNT AND MODAL IDENTIFICATION

2.1. Shaking Table Tests

The tested structure, as shown in Figure 1, is a 1:20 scale model of a typical high-rise residential building in Hong Kong with the transfer plate system and large open-space at the lower stories, from which it can be seen that the accelerometers distribute nearly uniformly along the vertical direction. The prototype building is a 38-storey reinforced concrete structure with 34 stories typical floors supported by a transfer plate and a three-level podium. The scaled model, which is 2.370m long, 2.160m wide and 6.515m high, is constructed with No. 1-3 bottom floors, one transfer plate, No. 4-38 typical floors, and No. 39-42 top machine floors. In the model structure, sizes of the concrete beams, columns, slabs and shear walls and core walls are strictly fabricated following the dimensional scale ratio 1:20, and the structural materials (including additional masses and reinforcements) are selected according to the similitude law. The section area and number of reinforcements are designed to meet the requirement of the reinforcement ratio used in the prototype building.


Figure 1 Tested tall building model

The model structure was tested on a 5m × 5m, 6-DOF shaking table by exerting successively enhanced earthquake waves (minor earthquake, moderate earthquake, strong earthquake and super-strong earthquake excitations). Accordingly, it was subjected to seismic destroy extending from trifling, moderate, serious damage till to complete (nearly collapsed) damage. When the structure was subjected to minor earthquake excitations, fine 'hair-line' cracks were found in several structural members at the podium level (transfer plate). These cracks were barely noticeable with small width. When subjected to moderate earthquake excitations, cracks previously appeared under minor earthquake excitation propagated with slight increase in crack width. More importantly, new horizontal and diagonal cracks were found between floors No. 4 and 8 above the transfer plate, indicating the shift of structural damage to the stories above podium level. Under strong earthquake excitations, besides increase in the crack width and propagation of the cracks found in moderate earthquake excitations, more than 50 new cracks were found. Most of them appeared at stories above the transfer plate and at the middle and upper stories. When subjected to super-strong earthquake excitations, integrity of the structure was destroyed. The failure is mainly due to complete separation of an end shear wall at the vicinity above the transfer plate. Horizontal cracks appeared on the surfaces of the floor slabs in all the stories, with the severest cases at floors No. 4 to 10. More detailed descriptions on the shaking table tests and observed damage of the tested structure refer to Li et al. (2006).

After experiencing each level of earthquake excitations, the structure was subjected to 20-minute white-noise random excitation of low intensity at its base to generate ambient vibration, and the acceleration responses under the ambient vibration were measured for modal damage identification. Because the level of the white-noise random excitation is considerably low, it is regarded that the structure keeps the same damage state during the ambient vibration. The acceleration responses were measured with a sampling rate of 100 Hz and only the records in one horizontal direction (referred to as X-direction) are used in the present study.

2.2. Modal Identification

The ambient vibration acceleration responses obtained from the structure after experiencing each level of earthquake excitations are used for modal identification. The output-only Complex Mode Indicator Function (CMIF) method (Ni et al. 2005) is applied to identify the modal parameters. Table 1 shows the identified natural frequencies of the first mode in X-direction. Due to the limited space, only the natural frequencies and modal shapes of the first translational modes in X-direction are given here and used for damage evaluation, though the translational modes in Y-direction and torsional modes are also identified. It is observed that the natural frequencies decrease with the increasing magnitude of earthquake excitation. The mode shapes of the first translational modes in X-direction for the tested structure after experiencing each level of earthquake excitations are illustrated in Figure 2, which will be used for damage evaluation.

Table 1 Identified natural frequencies for the 1st mode in X-direction

Case	CMIF method (Hz)
No damage (N)	4.61
Trifling damage (T)	4.55
Moderate damage (M)	4.32
Serious damage (S)	3.70
Complete damage (C)	2.58

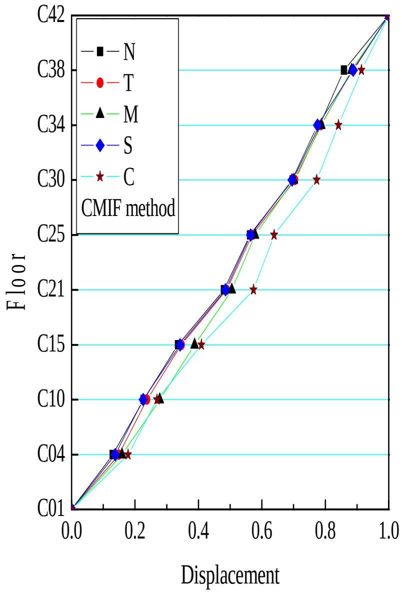

Figure 2 Identified mode shapes for the 1st mode in X-direction

3. SEISMIC DAMAGE IDENTIFICATION

In this section, five modal-based indices are constructed in terms of the measured natural frequencies and mode shapes for seismic damage identification. They are all structural model free.

3.1. Coordinate Modal Assurance Criterion (COMAC)

The COMAC index is defined as (Lieven and Ewins 1988)

$$COMAC\ (p) = \frac{\sum_{r=1}^{N} \left| (\phi_{pr})(\varphi_{pr}) \right|^2}{\sum_{r=1}^{N} (\phi_{pr})^2 \sum_{r=1}^{N} (\varphi_{pr})^2} \tag{1}$$

where p and r denote the modal coordinate and modal order, respectively; ϕ and φ represent the mode shape vectors before and after structural damage; and N indicate the total number of measured modes.

Figure 3 shows the COMAC vectors for the trifling damage, moderate damage, serious damage and complete damage cases, respectively. All the values are obtained using the modal shapes of the first translational mode in X-direction. In comparison with the visual inspection results of damage, it is found that the COMAC index can roughly indicate the damage locations (floors) except for the damage at floor No. C10.

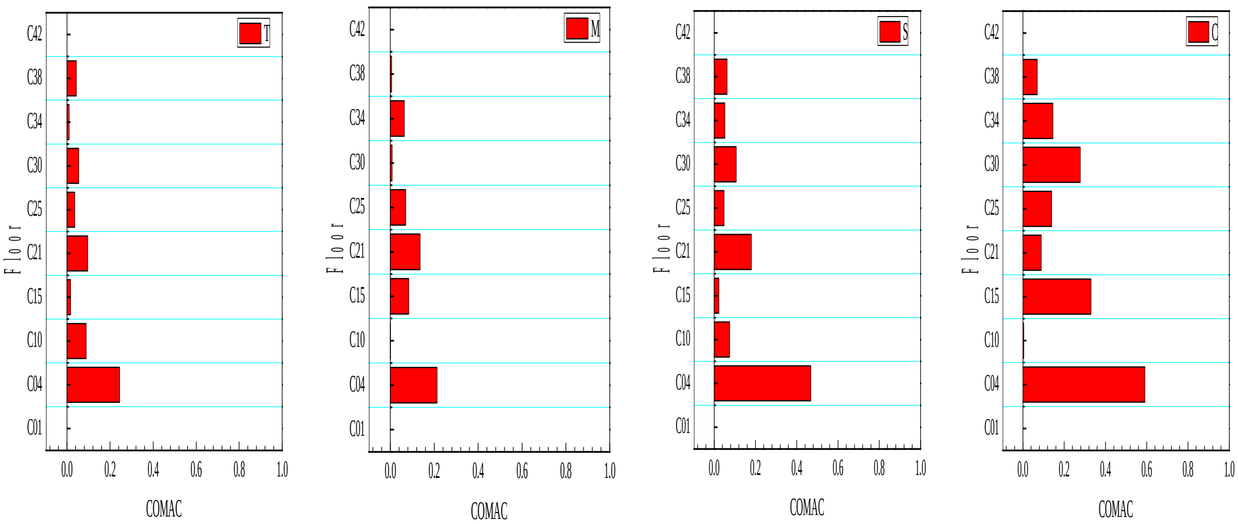

Figure 3 COMAC vectors for four damage cases

3.2. Mode Shape Based Z-Value

The *Z*-value damage index is defined as (Wang et al. 2000)

$$Z_i = \frac{index\ (i) - M\ (index\ )}{\sigma\ (index\ )} \tag{2}$$

in which,

$$Index\ _j\ (i) = \frac{|\ C_j^d\ (i) - C_j^u\ (i)\ |}{\sum_i |\ C_j^d\ (i) - C_j^u\ (i)\ |} \tag{3}$$

$$C_j(i) = \frac{\phi_j(i-1) + \phi_j(i+1) - 2\phi_j(i)}{2l_i^2} \tag{4}$$

where i and j denote the mode coordinate and mode order, respectively; l_i is the distance between the ith and (i+1)th mode coordinates; σ and M denote the standard deviation and mean value of the *Index* sequence.

The *Z*-value vectors obtained using the modal shapes of the first translational mode in X-direction are shown in Figure 4 for the four damage cases. From this figure it is seen that the *Z*-value index does not give a consistent indication on the damage locations for the four cases with successively increased damage severity. Moreover, the damage locations indicated by the *Z*-value index do not conform to the visual inspection results of damage. In conclusion, the *Z*-value index constructed using the modal shapes of the first translational mode in X-direction fails to identify the damage.

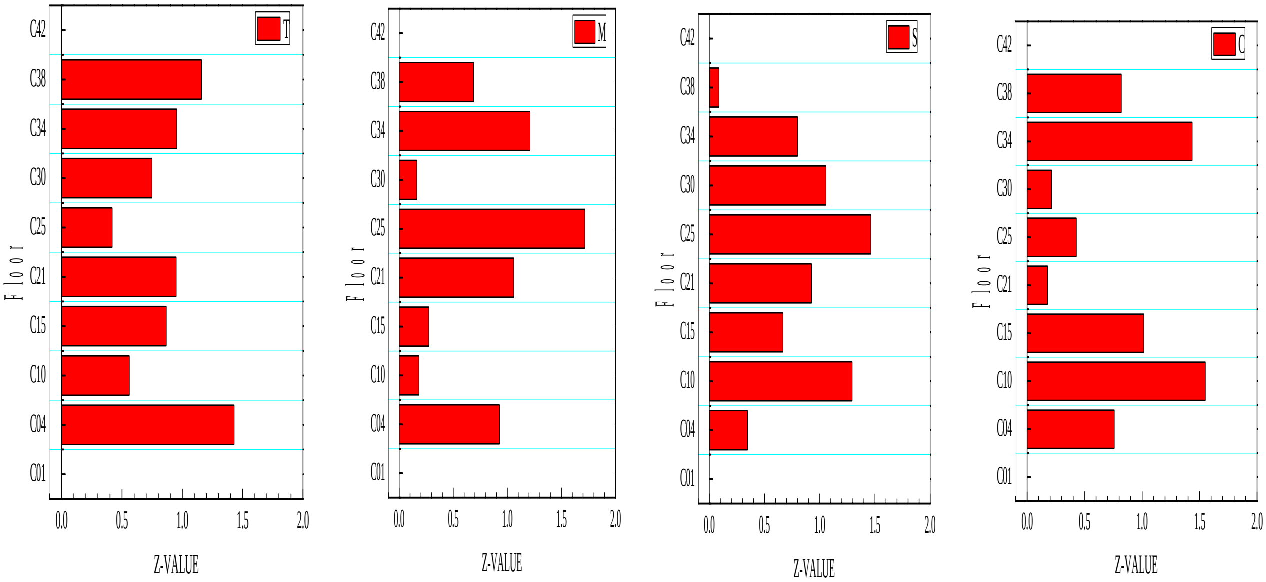

Figure 4 Z-value vectors for four damage cases

3.3. Modal Flexibility Damage Index (MFDI)

The dynamic modal flexibility matrix is defined as

$$[F] = [\Phi]^T[\Lambda]^{-1}[\Phi] \tag{5}$$

in which [Λ] and [Φ] are the eigenvalue and eigenvector matrices, respectively. The elements in the matrix [F] can be expressed as

$$F_{ij} = \begin{cases} \sum_r \frac{1}{\omega_r^2}\phi_{ir}\phi_{jr} & i \neq j \\ \sum_r \frac{1}{\omega_r^2}\phi_{ir}^2 & i = j \end{cases} \tag{6}$$

where ω_r represents the modal frequency of the rth mode. In the present study, the modal flexibility damage index is defined as the percentage change of the diagonal elements in [F] (Ni et al. 2008)

$$MFDI_i = \frac{|F_{ii}^d - F_{ii}^u|}{F_{ii}^u} \tag{7}$$

The MFDI vectors obtained using the natural frequencies and modal shapes of the first translational mode in X-direction are shown in Figure 5 for the four damage cases. The MFDI index correctly indicates damage locations (floors), conforming favorably to the visual inspection results of damage. From both the identification and observation results, it is found that the earthquake-induced cracks mainly concentrate on the lower floors and the transfer plate in the trifling and moderate damage cases. The cracks gradually expand to the whole structure in the serious and complete damage cases where the MFDI index attains to large values at the upper floors (C25 to C42).

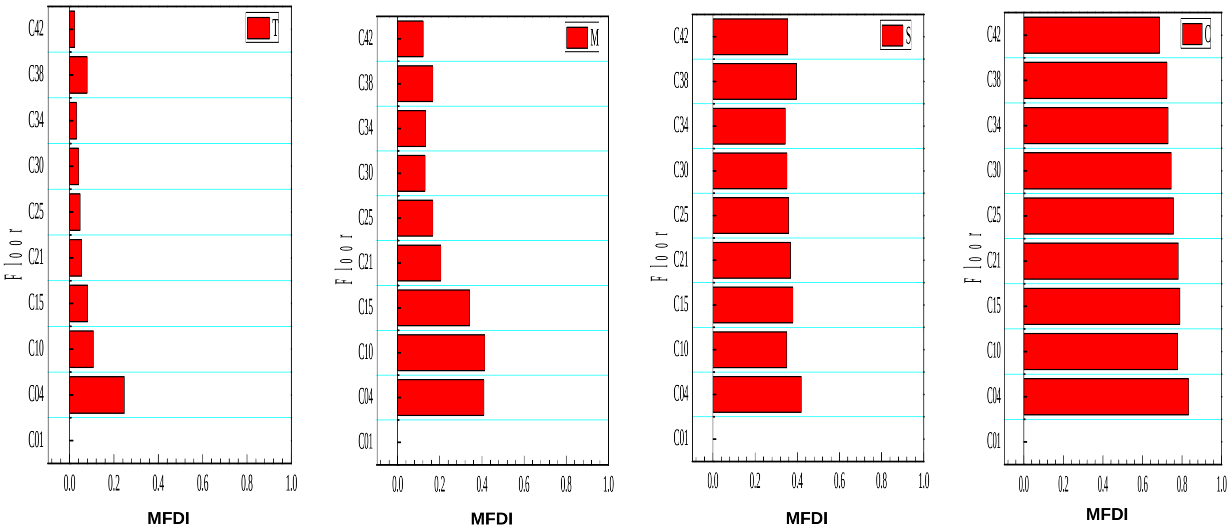

Figure 5 MFDI vectors for four damage cases

3.4. Story Damage Index (SDI)

By defining damage in a building as the reduction in percentage of story stiffness before and after damage, the story damage index for the lth story can be expressed as (Wang et al. 2007)

$$SDI_l = 1 - \frac{k_l^*}{k_l} = 1 - \frac{\omega_j^{*2} \sum_{i=l}^{N} \frac{m_i \phi_{ij}^*}{\Delta \phi_{lj}^*}}{\omega_j^2 \sum_{i=l}^{N} \frac{m_i \phi_{ij}}{\Delta \phi_{lj}}} = 1 - \frac{\frac{\omega_j^{*2}}{\Delta \phi_{lj}^*} \sum_{i=l}^{N} m_i \phi_{ij}^*}{\frac{\omega_j^2}{\Delta \phi_{lj}} \sum_{i=l}^{N} m_i \phi_{ij}} \tag{8}$$

in which

$$k_l = \omega_j^2 \sum_{i=l}^{N} \frac{m_i \phi_{ij}}{\Delta \phi_{lj}} \qquad j = 1, 2, \ldots, N \tag{9}$$

$$\Delta \phi_{lj} = \begin{cases} \phi_{lj} - \phi_{(l-1)j} & for\ l = 2, 3, \ldots, N \\ \phi_{lj} & for\ l = 1 \end{cases} \tag{10}$$

where k_l and m_i are the stiffness at the lth floor and the mass at the ith floor for an N floor shear building frame; ϕ_{ij} is the ith element of the jth mode shape; and the asterisk (*) denotes the damage state.

The SDI vectors obtained using the natural frequencies and modal shapes of the first translational mode in X-direction are shown in Figure 6 for the four damage cases. By comparing the identified damage and the true damage observed during the tests, it is found that the SDI index can correctly indicate the damage locations (floors). Same as the MFDI index, the SDI index also indicates the evolution trend of damage along the elevation of the tested structure. The SDI index offers an easier way to identify the damage due to its simple expression and less modal parameters in need for damage evaluation.

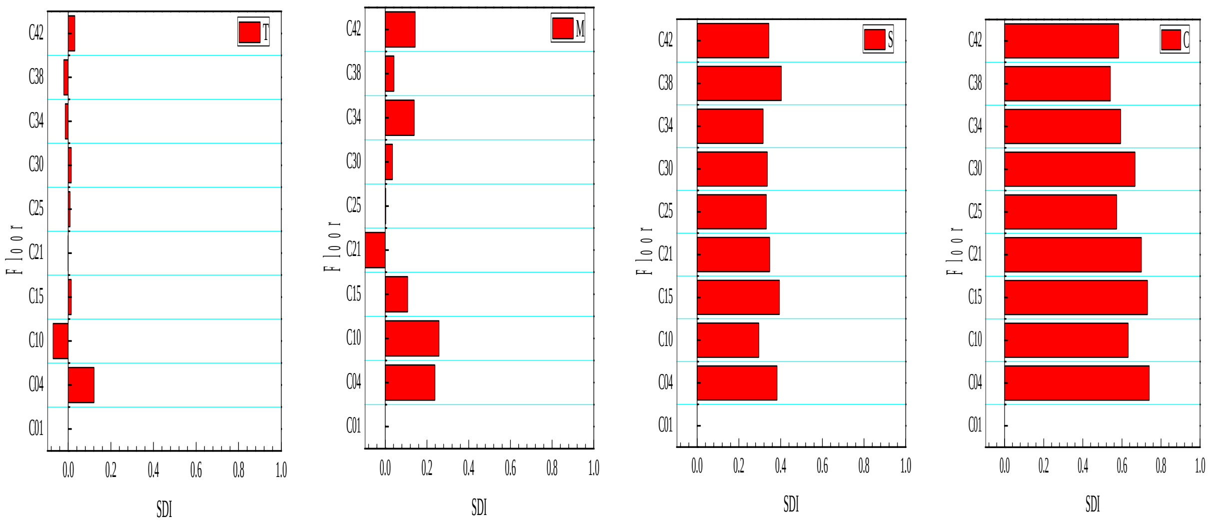

Figure 6 SDI vectors for four damage cases

3.5. Approximate Story Damage Index (ASDI)

By assuming a uniform distribution of floor masses along the building height, the approximate story damage index for the lth story can be derived from Equation (8) as

$$ASDI_l = 1 - \frac{\omega_j^{*2} \sum_{i=l}^{N} \frac{\phi_{ij}^*}{\Delta\phi_{lj}^*}}{\omega_j^2 \sum_{i=l}^{N} \frac{\phi_{ij}}{\Delta\phi_{lj}}} = 1 - \frac{\frac{\omega_j^{*2}}{\Delta\phi_{lj}^*} \sum_{i=l}^{N} \phi_{ij}^*}{\frac{\omega_j^2}{\Delta\phi_{lj}} \sum_{i=l}^{N} \phi_{ij}} \tag{11}$$

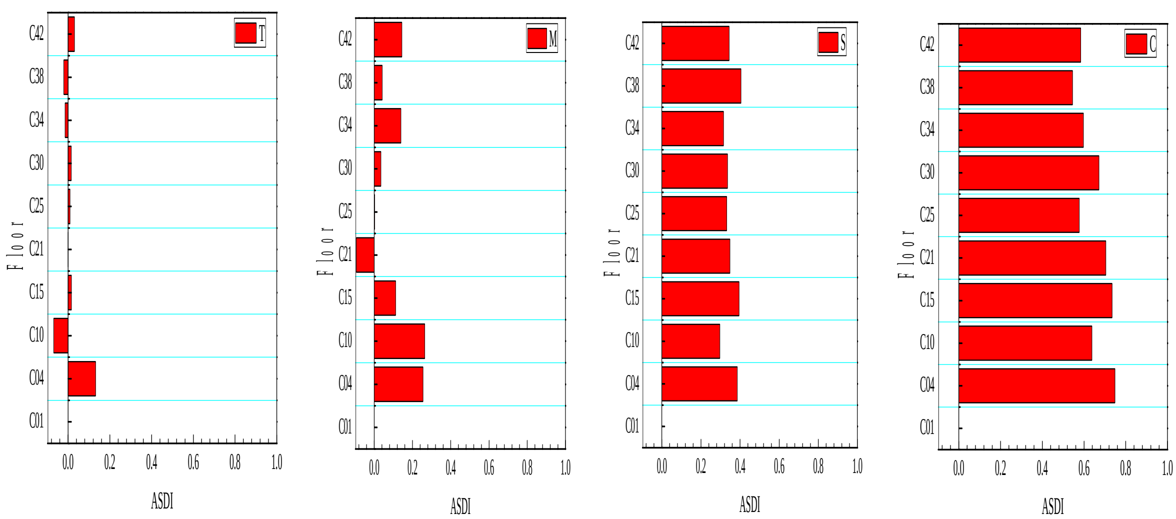

Figure 7 ASDI vectors for four damage cases

Figure 7 illustrates the ASDI vectors obtained using the natural frequencies and modal shapes of the first translational mode in X-direction. Although the tested structure has a nonuniform mass distribution along the height, the ASDI index provides almost the same damage identification results as the SDI index for all the four damage cases. It is therefore concluded that the ASDI index without considering the floor mass is still able to provide reliable damage identification for nonuniformly distributed structures.

4. CONCLUSIONS

An experimental investigation of a 38-story structural model has been conducted to study the applicability of various modal-based indices for seismic damage evaluation of tall building structures based on post-earthquake ambient vibration measurement. All the modal-based indices employed in this study can be constructed without use of structural finite element model. The experiment has been designed to be able to examine the capability of these indices in identifying different levels of damage. It is found that when using only the modal information from the first mode, the modal flexibility damage index (MFDI), story damage index (SDI) and approximate story damage index (ASDI) perform much better than the coordinate modal assurance criterion (COMAC) and mode shape based *Z*-value. Especially, the ASDI index is able to identify structural damage at various severities even for the structures with nonuniformly distributed floor masses.

ACKNOWLEDGMENTS

The work described in this paper was supported in part by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 5263/08E) and partially by a grant from The Hong Kong Polytechnic University through the Development of Niche Areas Programme (Project No. 1-BB68). The shaking table tests were conducted by a joint team from The Hong Kong Polytechnic University and the Institute of Engineering Mechanics of China Seismological Bureau (Coordinator: Dr. S.S.E. Lam).

REFERENCES

Ko, J.M. and Ni, Y.Q. (1999). Development of vibration-based damage detection methodology for civil engineering structures. *Proceedings of the First International Conference on Structural Engineering*, Kunming, China, 37-56.

Li, C.S., Lam, S.S.E., Zhang, M.Z. and Wong, Y.L. (2006). Shaking table test of a 1:20 scale high-rise building with transfer plate system. *ASCE Journal of Structural Engineering* **132:11**, 1732-1744.

Lieven, N.A.J. and Ewins, D.J. (1988). Spatial correlation of mode shapes: the coordinate modal assurance criterion (COMAC). *Proceedings of the Sixth International Modal Analysis Conference*, Kissimmee, Florida, USA, 690-695.

Ni, Y.Q., Fan, K.Q., Zheng, G. and Ko, J.M. (2005). Automatic modal identification and variability in measured modal vectors of a cable-stayed bridge. *Structural Engineering and Mechanics* **19:2**, 123-139.

Ni, Y.Q., Zhou, H.F., Chan, K.C. and Ko, J.M. (2008). Modal flexibility analysis of cable-stayed Ting Kau Bridge for damage identification. *Computer-Aided Civil and Infrastructure Engineering*, **23:3**, 223-236.

Sohn, H., Farrar, C.R., Hemez, F.M., Shunk, D.D., Stinemates, D.W., Nadler, B.R. and Czarnecki, J.J. (2004). A review of structural health monitoring literature: 1996-2001. *Report No. LA-13976-MS*, Los Alamos National Laboratory, Los Alamos, USA.

Wang, B.S., Liang, X.B., Ni, Y.Q. and Ko, J.M. (2000). Comparative study of damage indices in application to a long-span suspension bridge. *Advances in Structural Dynamics*, J.M. Ko and Y.L. Xu (eds.), Elsevier Science Ltd., Oxford, UK, Vol. II, 1085-1092.

Wang, J.F., Lin, C.C. and Yen, S.M. (2007). A story damage index of seismically-excited buildings based on modal frequency and mode shape. *Engineering Structures* **29:9**, 2143-2157.