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STRUCTURAL HEALTH MONITORING METHODOLOGY CONSISTING OF TWO STAGES WITH DIFERENT PURPOSES

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SUMMARY

This paper presents a unique two-stage-based methodology of detecting how the reduction in story stiffness of a damaged or old building is. The purpose of the first stage is to determine whether the damage exists or not and detect its location if the damage exists. In this stage, the modal vector of a structure is estimated with the aid of the proper orthogonal decomposition (POD) technique. The changes of modal vector provides useful information in detecting the damage locations.The purpose of the second stage of the proposed methodology is to quantify the damage. In this stage, system identification is conducted for the subsystems representing the behavior of those selected stories which may be damaged. For that purpose, the natural frequencies of the subsystems are identified by means of subspace identification technique. Such natural frequencies are helpful in evaluating story stiffness. The validity of the proposed methodology is demonstrated by conducting computer simulations and scale-model experiments.

INTRODUCTION

During the last two decades system identification technique has been more and more integrated into civil engineering field. Along with the recent remarkable development of structural health monitoring and structural control, system identification is expected to play more significant role at the future stage of the civil engineering field. Structural health monitoring is classified into the following four levels [1 - 4)] : (1) determining whether a damage exits in a structure; (2) detecting where the damage is located; (3) quantifying how severe the damage is; and (4) estimating the remaining lifetime of a structure. Most of structural health monitoring methods are aimed at quantifying how severe the damage of a structure is. If several different methods corresponding to the above-mentioned four levels are available, structural health monitoring can be more useful means.

This paper presents a unique two-stage-based methodology of detecting how the reduction in story stiffness of a damaged or old building is. The purpose of the first stage is to determine whether the

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damage exists or not and detect its location if the damage exists. On the other hand, the purpose of the second stage of the proposed methodology is to quantify the damage.

Unlike most of the conventional methodologies[5, 6)], the proposed scheme does not need to make simultaneous measurements of all of the floor responses. At its first stage, this scheme estimates an acceleration-based modal vector for a structural system integrating the ground surface acceleration with the aid of POD (proper orthogonal decomposition) technique [7 - 10)], and quantifies how the inter-story values of the acceleration-based modal vector increase in conducting the damage detection and assessment, then determining whether the damage exists and searching for where the damage is located. At the second stage, the natural frequencies of subsystems representing only damage-suspicious stories are estimated based on a subspace identification technique [11 - 13)] based methodology proposed by the authors [11)]. In estimating the natural frequencies of such subsystems, that methodology needs only the acceleration responses of the three stories containing the story in question and its upper and lower stories. Based on these estimated natural frequency values compared with those in the undamaged state, it is determined how the reduction in story stiffness is. The validity of the proposed methodology is demonstrated by conducting computer simulations and scale-model experiments.

STRUCTURAL HEALTH MONITORING HAVING TWO STAGES

The proposed scheme has two stages. The aim of the first stage of the proposed methodology is to determine whether the damage exists or not and detect its location if the damage exists. In this stage, the modal vector is estimated with the aid of the proper orthogonal decomposition (POD) technique [7 - 10)]. The POD technique is effectively utilized to detect the modal vectors based on absolute acceleration response data. In doing this, a structure is divided into several units consisting of multi-story and the modal vector for each unit is estimated. The changes of modal vector provides useful information in detecting the damage locations. For the purpose of taking out effect of higher mode, this paper deals with absolute acceleration response data passing through the bandpass-filter covering the range of the first modal frequency of a structure.

The purpose of the second stage of the proposed methodology is to quantify the damage state and location. In this stage, system identification is conducted for the subsystems representing the behavior of those selected stories which may be damaged. For that purpose, the natural frequencies of the subsystems are identified by means of subspace identification technique. Such natural frequencies are helpful in evaluating the story stiffness.

The proposed methodology consists of the following procedures:

(I) Estimate the first modal vector of each unit by means of POD.
(II) Obtain the whole shape of the modal vector.
(III) Quantify the increase rate of inter story values of the estimated modal vector to search for the damage location.
(IV) Identify the natural frequency of a subsystem representing the damage-suspicious story with the aid of subspace identification technique.
(V) Compare the above-estimated natural frequency with that in the undamaged condition and evaluate the story stiffness reduction.

In the above procedures consisting of Processes I to V, the first three processes represent the first stage of the proposed health monitoring scheme, while IV and V present the second stage. More detailed procedure of each of Processes is explained in the following, assuming that a N-story building is divided into L units, each unit consisting of M stories.

Process I:

The correlation matrix of absolute acceleration response vector going through the bandpass filter corresponding to the first mode is given by

$$\boldsymbol{R}_\ell = E\left[\boldsymbol{Y}_\ell \, \boldsymbol{Y}_\ell^{\,T}\right] \tag{1}$$

with

$$\boldsymbol{Y}_\ell = \left[\begin{array}{ccc} \boldsymbol{y}_\ell(0) & \cdots & \boldsymbol{y}_\ell(N) \end{array}\right]$$

$$\boldsymbol{y}_\ell(j) = \begin{bmatrix} \ddot{x}_{i+M-1}(j) \\ \vdots \\ \ddot{x}_i(j) \end{bmatrix}$$

For the unit including the first story

$$\boldsymbol{y}_1(j) = \begin{bmatrix} \ddot{x}_M(j) \\ \vdots \\ \ddot{x}_1(j) \\ \ddot{x}_0(j) \end{bmatrix}$$

in which $x_i(j)$ represents the bandpass-filtered absolute acceleration response of i th story at discrete time $k\,\Delta t$, $x_0(j)$ represents the bandpass-filtered ground acceleration response at discrete time $k\,\Delta t$. Following the POD technique, the eigen vector corresponding to the largest eigen value of the correlation matrix $\boldsymbol{R}_\ell$ gives the first modal vector.

Process II:

Utilizing the estimated modal vectors of each unit $\boldsymbol{\varphi}_\ell$, the modal vector as a whole structure, $\boldsymbol{\varphi}$, can be provided by

$$\boldsymbol{\varphi} = \begin{bmatrix} \boldsymbol{\varphi_L} \\ \alpha_{L-1} \times \boldsymbol{\varphi_{L-1}} \\ \vdots \\ \left(\prod_{\ell=1}^{L-1} \alpha_\ell\right) \times \boldsymbol{\varphi_1} \end{bmatrix} \tag{2}$$

where

$$\alpha_\ell = 0.5 \times \left(\frac{\varphi_{1,\,\ell+1}}{\varphi_{M-1,\,\ell}} + \frac{\varphi_{2,\,\ell+1}}{\varphi_{M,\,\ell}}\right)$$

in which $\boldsymbol{\varphi}_\ell$ represents the modal vector for the unit ℓ, and $\varphi_{i,\ell}$ represents the i th component of the modal vector $\boldsymbol{\varphi}_\ell$. The obtained modal vector has been normalized so that the Euclidean norm should be equal to one.

Process III:
The increase rate in the modal vector is estimated in the following way:

$$\beta_i = \frac{\tilde{\psi}_i - \psi_i}{\psi_i} \tag{3}$$

with

$$\psi_i = \left| \phi_i - \phi_{i-1} \right|$$

$$\tilde{\psi}_i = \left| \tilde{\phi}_i - \tilde{\phi}_{i-1} \right|$$

where ϕ_i and $\tilde{\phi}_i$ represent the element corresponding to the ith story of the first modal vector, respectively, in the undamaged state and damage-suspicious state.

Process IV:
Express the behavior of a damage-suspicious story in the following way as a subsystem representing the story in question and estimate the natural frequency of this subsystem by means of subspace identification technique:

$$\dot{X}_i = A_i X_i + B_i U_i \tag{4}$$

with

$$A_i = \begin{bmatrix} -\dfrac{c_i}{m_i} & -\dfrac{k_i}{m_i} \\ 1 & 0 \end{bmatrix}, \qquad B_i = \begin{bmatrix} -1 & \dfrac{c_{i+1}}{m_i} & \dfrac{k_{i+1}}{m_i} \\ 0 & 0 & 0 \end{bmatrix},$$

$$X_i = \left[\dot{x}_{f\,i} \quad x_{f\,i} \right]^T, \qquad U_i = \left[\ddot{x}_{g\,i} \quad u_{v\,i} \quad u_{d\,i} \right]^T,$$

$$\ddot{x}_{f\,i} = \frac{s^2\,\ddot{d}_i}{(s+\alpha)^2}, \qquad \dot{x}_{f\,i} = \frac{s^2\,\dot{d}_i}{(s+\alpha)^2}, \qquad x_{f\,i} = \frac{s^2\,d_i}{(s+\alpha)^2},$$

$$\ddot{x}_{g\,i} = \frac{s^2\,(\ddot{x}_{i-1} + \ddot{x}_g)}{(s+\alpha)^2}, \qquad u_{v\,i} = \frac{s\,\ddot{d}_{i+1}}{(s+\alpha)^2}, \qquad u_{d\,i} = \frac{\ddot{d}_{i+1}}{(s+\alpha)^2}$$

where s represents the Laplace operator and thus $s^2/(s+\alpha)^2$, $s/(s+\alpha)^2$ and $1/(s+\alpha)^2$ represent high-pass filter, integral filter[14)] and low-pass filter, respectively. These three filters can be dealt with in the time-domain by converting them into the state-space equations. In order to estimate the natural frequency of each subsystem representing those selected stories which may be damaged, subspace identification technique is employed.

Process V:

Utilizing two different natural frequency values of a subsystem in question, one for the undamaged case and the other for the damage-suspicious case, the index defined in the following way representing the story stiffness reduction is calculated:

$$\upsilon_i = \frac{\tilde{\omega}_i^{\,2}}{\omega_i^{\,2}} \tag{5}$$

where ω_i and $\tilde{\omega}_i$ are the subsystem natural frequencies, respectively, in the undamaged and damage-suspicious states. The above V and IV procedures are repeatedly processed with respect to all of the damage-suspicious stories.

NUMERICAL EXAMPLES

To demonstrate the effectiveness of the proposed approach, numerical simulations are conducted for a 20-story building model. The parameters with respect to the building are shown in Table 1. The first three fundamental frequencies of the 20-story building model are: 0.56, 1.38 and 2.20 Hz. The structural damping matrix is assumed to be proportional to the stiffness matrix so as to have the damping ratio of 0.02 with respect to the first mode.

Table 1 Parameters of 20-story building model

Story	Mass [t]	Stiffness [kN/m]	Damping [kN・s/m]	Height [m]
1	980	3.49×10^6	3.94×10^4	4.5
2	980	3.68×10^6	4.16×10^4	3.7
3	980	3.32×10^6	3.75×10^4	3.7
4	980	3.03×10^6	3.42×10^4	3.7
5	980	2.79×10^6	3.15×10^4	3.7
6	980	2.61×10^6	2.95×10^4	3.7
7	980	2.44×10^6	2.76×10^4	3.7
8	980	2.28×10^6	2.58×10^4	3.7
9	980	2.13×10^6	2.41×10^4	3.7
10	980	1.99×10^6	2.25×10^4	3.7
11	980	1.83×10^6	2.07×10^4	3.7
12	980	1.67×10^6	1.89×10^4	3.7
13	980	1.53×10^6	1.73×10^4	3.7
14	980	1.38×10^6	1.56×10^4	3.7
15	980	1.23×10^6	1.39×10^4	3.7
16	980	1.09×10^6	1.23×10^4	3.7
17	980	9.29×10^5	1.05×10^4	3.7
18	980	7.61×10^5	8.60×10^3	3.7
19	980	5.71×10^5	6.45×10^3	3.7
20	1568	3.39×10^5	3.83×10^3	3.7

Two different damaged model structures are dealt with. As the first model structure, referred to as Model D1, the stiffness values of the first, eleventh and twentieth stories are assumed to reduce to 10% smaller than the original values. As the second model, referred to as Model D2, the stiffness values of the ninth and eleventh are 10% smaller and the stiffness of the tenth story is 20% smaller than the original values. In conducting numerical simulations, it is assumed that the response data are the acceleration responses and ground surface acceleration measured for the duration of 30 seconds, in which interval the structure is subjected to a ground acceleration represented by a bandlimited white noise. Each of the measured data is assumed to involve a white measurement noise of which the standard deviation has the magnitude of 1% of that of the real responses. In conducting the measurement, the twenty-story model building is divided into four units, which are the unit from the twenties to fifteenth stories, the unit from the sixteenth to tenth stories, the unit from the eleventh to fifth stories and the unit from the sixth to first stories. The measurements are repeated five times with the sampling interval Δt =0.005 sec for each unit.

For the purpose of taking out the measurement noises, the data are made to go through a band-pass filter during 0.3 to 0.7 Hz. This frequency range has been determined reflecting the fact that the natural frequency 0.56 Hz of the original undamaged model (Model ND). By applying POD technique to those data which have been through this band-pass filter, the modal vector of each unit is estimated. From the modal vector thus estimated, the acceleration-based modal vector written as the form given by Eq. 2 is

Table 2 Estimated modal vector

	Mode vector		
Story	Model ND	Model D1	Model D2
Ground	0.0056	0.0050	0.0055
1	0.0085	0.0084	0.0084
2	0.0113	0.0113	0.0111
3	0.0143	0.0144	0.0141
4	0.0176	0.0178	0.0173
5	0.0209	0.0212	0.0206
6	0.0249	0.0253	0.0245
7	0.0297	0.0300	0.0292
8	0.0345	0.0348	0.0339
9	0.0395	0.0397	0.0392
10	0.0445	0.0446	0.0454
11	0.0498	0.0504	0.0510
12	0.0552	0.0557	0.0563
13	0.0608	0.0611	0.0616
14	0.0664	0.0665	0.0670
15	0.0720	0.0720	0.0724
16	0.0777	0.0774	0.0778
17	0.0833	0.0829	0.0832
18	0.0889	0.0882	0.0885
19	0.0944	0.0935	0.0937
20	0.1002	0.0997	0.0992

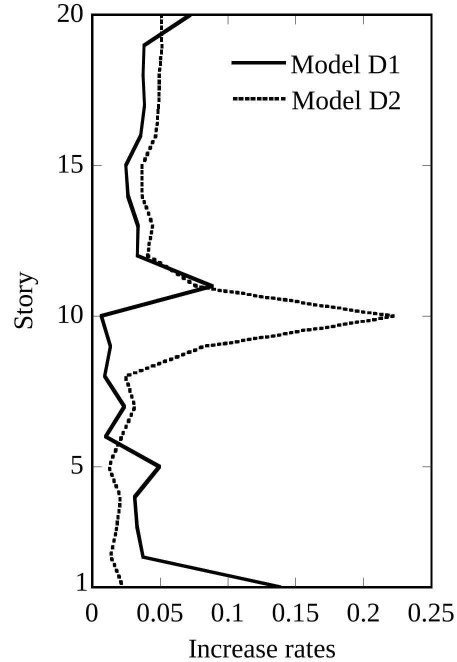

Figure 1　Increase rates

Table 3　Estimated damage location and level of Model D1

Story	ω_i^2	$\tilde{\omega}_i^2$	υ_i
1	3619	3222	0.891
11	1877	1699	0.905
20	205	184	0.898

Table 4　Estimated damage location and level of Model D2

Story	ω_i^2	$\tilde{\omega}_i^2$	υ_i
9	2191	1988	0.907
10	2022	1672	0.827
11	1877	1678	0.893

calculated. Table 2 demonstrates the undamaged-state modal vector values for Model ND as well as thevalues for Models D1 and D2. These values are normalized so as to have Euclidean norm of 1.0. The values are obtained by averaging the data obtained by the five repeated measurements.

Based on the values provided by Table 2, the increase rates of interstory indices are calculated. Fig. 1 depicts these calculated increase rates, thus indicating the damaged story locations, the twenties, eleventh and first stories for Model D1 and the eleventh, tenth and ninth stories for Model D2. Tables 3 and 4 show the square values of ω_i and $\tilde{\omega}_i$ and υ_i .

EXPERIMENTAL VERIFICATION

Experiments are conducted using the scale model representing a 8-story building shown Fig. 2. The damages are assumed to occur in the second and third stories. These damages are physically simulated by taking away four slender columns out of the original six columns in the second and third stories so as to make the second and third stories’ stiffnesses about 80% of the original values. These eight stories are divided into two units: one is from the eighth to forth stories and the other is from the fifth to first stories. The scale model is excited by the ground surface movement having bandlimitted white-noise through a shaking table. The data are measured during fifteen seconds with the sampling interval of 0.005 sec by repeating the experimental measurements in the same way as the numerical simulation presented in the previous section.

In order to remove the measurement noise effect from the measured data at the first stage, the measured data are made to go through the band-pass filter having the frequency range from 1.1 to 1.5 Hz. This frequency range has been determined based on the fact that the undamage-conditioned model structure has a natural frequency of 1.3 Hz. Applying POD technique to such bandpass-filtered data, the modal vector of each unit is calculated. The obtained undamaged and damaged modal vectors, which are both normalized so as to have the Euclidean norm of 1.0, is presented in Table 5. Fig.3 successfully indicates the great possibility of damages in the second and third stories judging from the large increase rates of interstory values in the second and third stories.

From the above results, the procedures for the second stage are processed for the second and third stories. The estimated undamaged and damaged stiffness indices for the second and third stories are shown and then the reduction in the story stiffness values are presented in Table 6. This result demonstrates that the proposed scheme effectively works in conducting structural health monitoring.

(a) Photograph of experimental model

(b) Photograph of damage part

Figure 2 Experimental model

Table 5 Estimated mode vectors

	Mode vectors	
Story	Without damage	with damage
Ground	-0.0012	0.0009
1	0.0279	0.0272
2	0.0573	0.0603
3	0.0840	0.0894
4	0.1077	0.1103
5	0.1453	0.1444
6	0.1774	0.1750
7	0.1956	0.1914
8	0.2061	0.2011

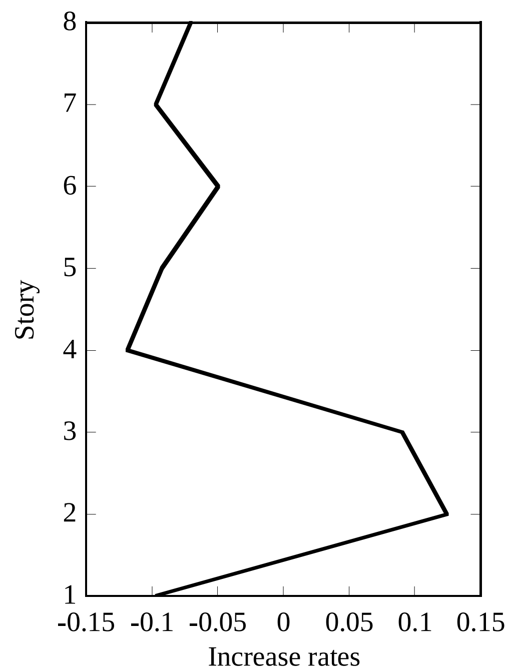

Figure 3 Increase rate

Table 6 Estimated damage location and level

Story	ω_i^2	$\tilde{\omega}_i^2$	υ_i
2	1692	1445	0.810
3	2009	1783	0.842

CONCLUDING REMARKS

This paper presents a unique two-stage-based methodology of detecting how the reduction in story stiffness of damaged building is. The purpose of the first stage is to determine whether the damage exists or not and detect its location if the damage exists. In this stage, the modal vector of a structure is estimated with the aid of the proper orthogonal decomposition technique. The changes of modal vector provide useful information in detecting the damage locations. On the other hand, the purpose of the second stage of the proposed methodology is to quantify the damage. In this stage, system identification is conducted for the subsystems representing the behavior of those selected stories which may be damaged. For that purpose, the natural frequencies of the subsystems are identified by means of subspace identification technique. Such natural frequencies are helpful in evaluating story stiffness. The effectiveness of the proposed methodology has been demonstrated by conducting the computer simulations and scale model experiments.

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