# Damage detection of shear building structure based on FRF response variation

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**Abstract.** This work studies the damage detection of a shear building structure from the change in the frequency response function (FRF) response before and after attaching an additional mass on the existing structure. The proper orthogonal modes (POMs) corresponding to the first proper orthogonal values (POVs) are extracted from the FRF data in the neighborhood of the first resonance frequency at two different states. The POM set at the first measurement is taken as the baseline datum, and it is compared with the other set extracted from the modified structure, in which additional mass was attached at all floors. It is shown that damage exists at a location to represent an abrupt change in the difference of the POMs at two different states. Furthermore, the method does not require baseline data in the intact state. The validity of the proposed method is illustrated in numerical examples and experimental works.

**Keywords:** damage detection, mode shape, resonance frequency, frequency response function, proper orthogonal decomposition, shear building.

## 1 Introduction

Most of the damage detection methods require knowing fundamental information for a structure without damage in order to establish a baseline for damage detection. The methods are not very suitable for practical structures, for which baseline data cannot be readily obtained. Practically, the structural performance should be evaluated only by the measured data at the damaged state.

During the past several decades, a significant amount of research has been conducted in the area of structural damage detection [1], [2]. Hola and Schabowicz [3] presented a survey of state-of-the-art non-destructive diagnostic techniques of testing building structures. Büyüköztürk et al. [4] provided the current state-of-the-art non-destructive test methods and their application to civil engineering and other engineering materials and structures. Sung et al. [5] and Koo et al. [6] provided damage detection methods of a five-story full-scale shear building by modal flexibility matrices obtained from acceleration responses. Utilizing the change in the

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first mode shape slopes and the sensitivity of modal parameters, Zhu et al. [7] presented a damage detection method for shear buildings. Morita and Teshigawara [8] presented the parameter identification method and damage estimation method using the results obtained from the shaking table test of a three-story large-scale steel structure. Escobar et al. [9] presented the transformation matrix method for damage detection in frame buildings. Vinayak et al. [10] handled the damage detection from modal parameter changes using a neural network approach. Xu et al. [11] identified the damage locations and severities using the statistical moment-based damage detection method. Xu et al. [12] provided a structural parameter identification and damage detection method using a displacement measurement time series. The method was carried out using a displacement-based neural network emulator and a parametric evaluation neural network.

Most approaches for the damage detection of shear building structures require baseline data for the intact state and have been limited to a theoretical approach like sensitivity analysis. The change in the FRF response before and after attaching the additional mass on the existing structure at measurement is utilized as the damage index in this study because it represents the change of the dynamic responses due to the additional mass. The POM is extracted from the FRF response data collected in the neighborhood of the first resonance frequency to be collected by the accelerometers. It is shown that damage exists at a location to represent an abrupt change in the difference of the POMs at two different states without baseline data at the intact state. The validity of the proposed method is illustrated in numerical examples and experimental works.

## 2 Damage detection algorithm

The dynamic behavior of a structure is assumed to be linear and approximately discretized for $n$ DOFs and can be described by the equations of motion

$$\mathbf{M}\ddot{u} + \mathbf{C}\dot{u} + \mathbf{K}u = \mathbf{f}(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{K}$, and $\mathbf{C}$ denote the $n \times n$ analytical mass, stiffness, and damping matrices at measurement, respectively, and $\mathbf{u} = \begin{bmatrix} u_1 & u_2 & \mathsf{L} & u_n \end{bmatrix}^T$. $\mathbf{f}(t)$ is the $n \times 1$ load excitation vector.

In order to establish the relationships between the FRF and modal parameters for successful modal testing, the substitution of $\mathbf{u} = \mathbf{U}e^{j\omega t}$ and $\mathbf{f} = \mathbf{F}e^{j\omega t}$ into Eqn. (1) leads to

$$\mathbf{K}_d \mathbf{U}(\omega) = \mathbf{F}(\omega) \tag{2}$$

where $\mathbf{K}_d$ indicates the dynamic stiffness matrix, $\mathbf{K}_d = -\omega^2 \mathbf{M} + j\omega \mathbf{C} + \mathbf{K}$, $\omega$ denotes the excitation frequency at measurement, and $j = \sqrt{-1}$. $\mathbf{H}_d(\omega) = \mathbf{K}_d^{-1}$ is the FRF matrix of the finite element model, whose elements can be the receptances.

The element $(\mathbf{H}_d)_{i,j}$ in the matrix $\mathbf{H}_d$ indicates a displacement response at station $i$ and a disturbing force at station $j$.

Taking Eqn. (1) as the dynamic equation of motion at the damaged state and expressing the additional mass matrix as $A\mathbf{M}$, the dynamic equation of the modified structure can be written as

$$\mathbf{K}_m(\mathbf{U}+A)\mathbf{U} =\mathbf{F} \tag{3}$$

where $\mathbf{K}_m$ indicates the modified dynamic stiffness matrix due to mass addition, $\mathbf{K}_m =$ -W$^2$ ( $\mathbf{M}$ + A ) $\mathbf{M}$ + $j$ W + $\mathbf{C}\,\mathbf{K}$. Inserting Eqn. (2) into Eqn. (3) and arranging the result gives

$$A\mathbf{U} =(A\mathbf{H})\,\mathbf{F} \tag{4}$$

where $A\mathbf{H}$ represents the variation in the FRF matrix because of mass addition under the same external force and

$$A\mathbf{H} = - \mathrm{W}^2 \mathbf{M} + A\mathbf{M} + j\,\mathrm{W}\,\mathbf{C} + \mathbf{K}\,\mathrm{W}\,A\mathbf{M}\,\mathbf{K}_d^{-1}.$$

The element $A H_{ij}$ represents the FRF variation in a displacement response at station $i$ and a disturbing force at station $j$. The equation shows that the FRFs are affected by the mass change, and the FRF variation before and after placing additional mass on the damage-expected structure can be utilized as an index to detect damage neglecting a little change of resonance frequencies due to mass addition.

## 3 Experimental verification by a shear building structure

The validity of the proposed method was considered in a four-story, one-bay by one-bay steel frame scale-model structure, shown in Fig. 1. A photograph showing the typical beam-column connection and bracing system is shown in Fig. 2. The four vertical columns were comprised of continuous steel angles L50 x 50 x 3 in height and were bolted to a concrete foundation with dimensions of $b$ x $w$ x $t$ = 500 x 500 x 150mm . The concrete foundation consists of four steel flanges bolted to each column, and the column was fastened to a massive concrete foundation. Four steel shim sheet squares represented the slab and measured approximately 290x 290x 3mm, and 2.08kg were placed on the flanges of the steel beams. Cross bracing was externally added within each story along two faces. All cross bracing members were made using 38x 3mm wide steel strips, each measuring approximately 505mm in length.

An impact hammer was used to excite the frame and hit the midspan point of the beam at the fourth floor in the bracing direction. This experiment was carried out using an accelerometer set to impact a fixed point of the fourth floor. The accelerometer set is composed of four accelerometers. Five measurement channels were utilized for data acquisition, including a channel for the impact hammer. The experiment was conducted using DYTRAN model 3055B1 uniaxial accelerometers along with a miniature transducer hammer Brüel & Kjaer model 8204 to excite the system. The data acquisition system was a DEWETRON model DEWE-43. The

FRFs relative to the reference location of the stationary accelerometer were measured. The measured data were collected as a FRF, which is defined as the ratio of the response of a system to its excitation force.
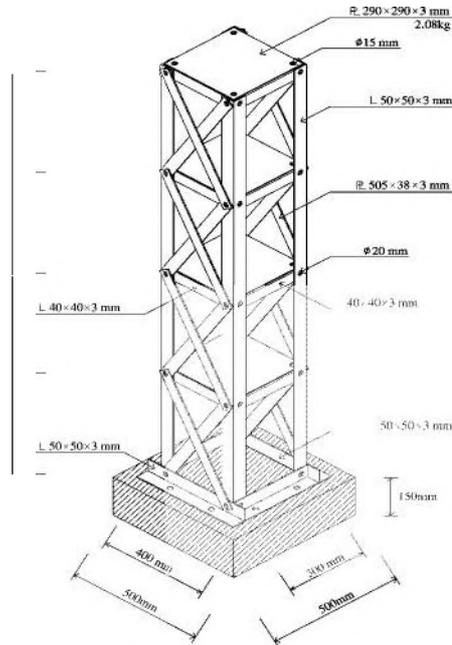


**Fig. 1.** Four-story steel frame structure.          **Fig. 2.** Steel frame model structure

The FRF is expressed as a function of the cross and auto spectra, which can readily be obtained from most multi-channel data acquisition systems. The cross spectrum is computed by multiplying the Fourier spectrum of a measured response by the complex conjugate of the Fourier spectrum of a known input:

$$\mathbf{G}_{xy}(w) = \mathbf{F}_x(w)\left(\mathbf{F}_y(w)\right)^* \tag{6}$$

where $\mathbf{G}_{xy(w)}$ denotes the cross spectrum, $\mathbf{F}_x(w)$ the Fourier spectrum of a measured response, and '*' is the complex conjugate. The auto spectrum is computed by multiplying the Fourier spectrum of the input by the complex conjugate of itself.

$$\mathbf{G}_{yy}(w) = \mathbf{F}_y(w)\left(\mathbf{F}_y(w)\right)^* \tag{7}$$

where $\mathbf{G_{yy}}(w)$ represents the auto spectrum. The FRF is then defined as the ratio of the cross and auto spectra.

$$\mathbf{H}w = \frac{\mathbf{G}_{xy}(w)}{\mathbf{G}_{yy}(w)} \tag{8}$$

where H$(w)$ is the FRF.

A mass dead load of 1 .68kg and a steel shim sheet of 2.08kg were uniformly placed on each floor of the frame. On each floor, the floor mass was stuck to the center of the floor using a magnet. The experimental work considered two damage cases by the removal of one bracing at the second and fourth floors. Two different measurement data sets from the damaged frame and the modified frame due to mass addition were collected. The former data set is regarded as the baseline data and is compared with the latter data set to find the response change. A FRF data set before attaching additional mass was collected and saved to compare it to the other FRF data set. Additional mass corresponding to 6.4% of the floor mass, including the steel shim sheet, was placed on all floors by magnets, and the other FRF data set was collected from the modified structure.



(a)



(b)
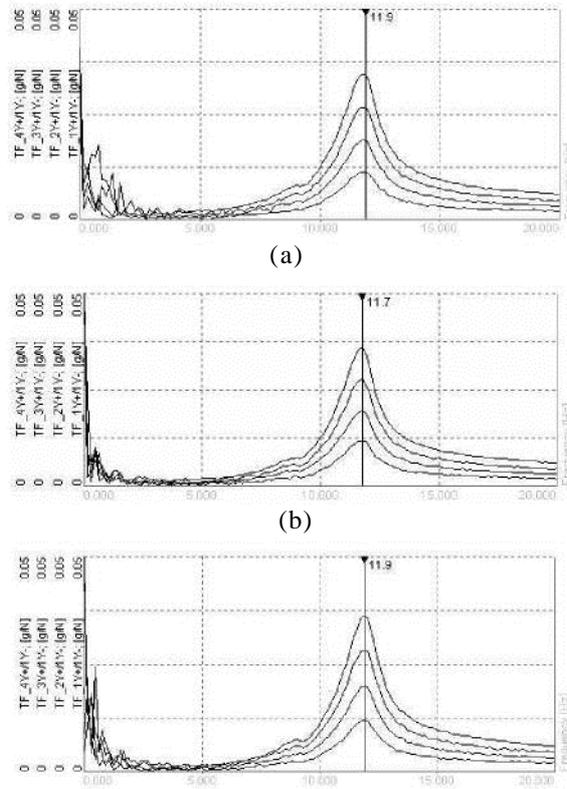


(b)

Fig. 3. Curves of FRF magnitude of the building model: (a) before placing the additional mass, (b) after placing the additional mass at the second floor, (c) after placing the additional mass at the fourth floor

Figure 3 illustrates the plot of FRF amplitude versus frequency at each floor of the building structure. It is shown that the amplitude of FRF at the fourth floor is the highest of all floors. And the first resonance frequency in the plots was rarely

changed depending on the additional mass and was observed in the neighborhood of 11.902Hz. A little variation in the resonance frequency due to the additional mass was neglected. The POMs were extracted from thirteen FRF data sets in the frequency range of $11.139- 12.97$ Hz , including the first resonance frequency. The POM corresponding to the first POV was considered. Figure 4 presents the POMs corresponding to the first POV and the variation in POM displacement before and after placing the additional mass. The POM curves at both states exhibit very similar tendencies and do not provide damage information, as shown in Figs. 4(a) and (b). The plots in Fig. 4(c) and (d) show that the abrupt change in the POM variation in the floor corresponds to the floors loosing one bracing.

As another experimental study, the damage detection of a building structure with a nonuniformly distributed floor mass was considered. The masses were 1.92, 1.92, 1.68 and 1.68 kg for the first, second, third and fourth floor, respectively. Two

cases of damage, in which one bracing at the second and fourth floors were lost, were studied. The additional mass of 0.24kg was placed by magnets as the previous



(a)                          (b)
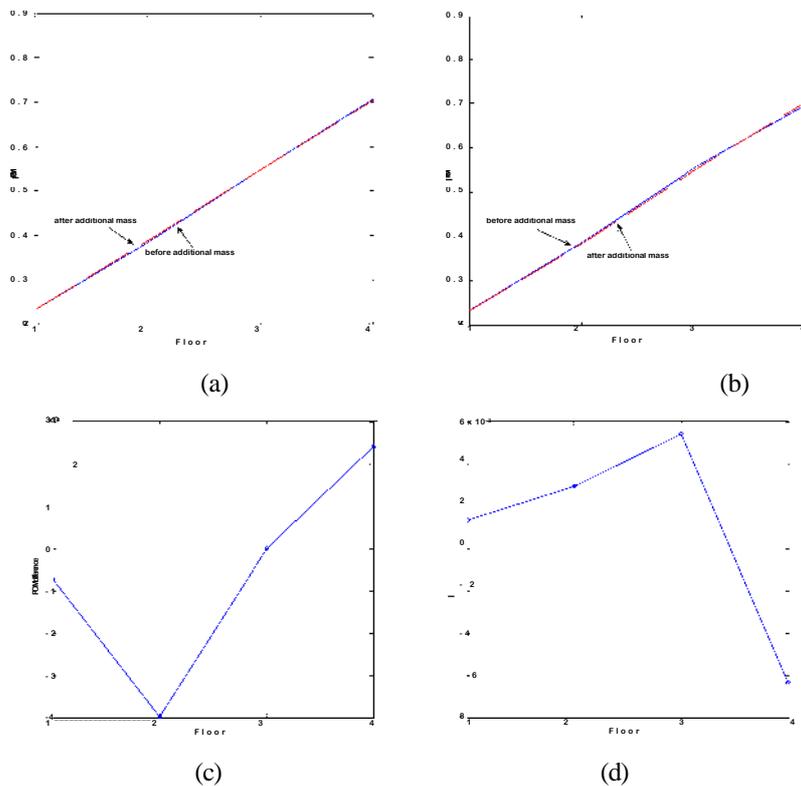
(c)                          (d)

Fig. 4. POM and its difference between two states (uniform mass distribution): (a) POM (damage at the second floor), (b) POM (damage at the fourth floor), (c) POM difference (damage at the second floor), (d) POM difference (damage at the fourth floor)

experiment. The POM corresponding to the first POV from the FRF data in the neighborhood of the first resonance frequency was calculated. The POMs and the difference between the POMs before and after attaching the additional mass are depicted in Fig. 5. The POM curves of the frame structure, which has damage at the second floor, as shown in Fig. 5(a), do not give any information on the damage location. The corresponding curves show that the damage at the fourth floor in Fig. 5(b) represent an abrupt change at the third and fourth floors. However, the POM curves cannot be utilized in detecting damage because they do not give consistent results, as in the other cases. The difference between the POMs before and after attaching the additional mass near the damage location abruptly changes, as shown in Figs. 5(c) and (d). It is expected that the difference, rather than the POM curve itself, can be utilized in detecting damage.
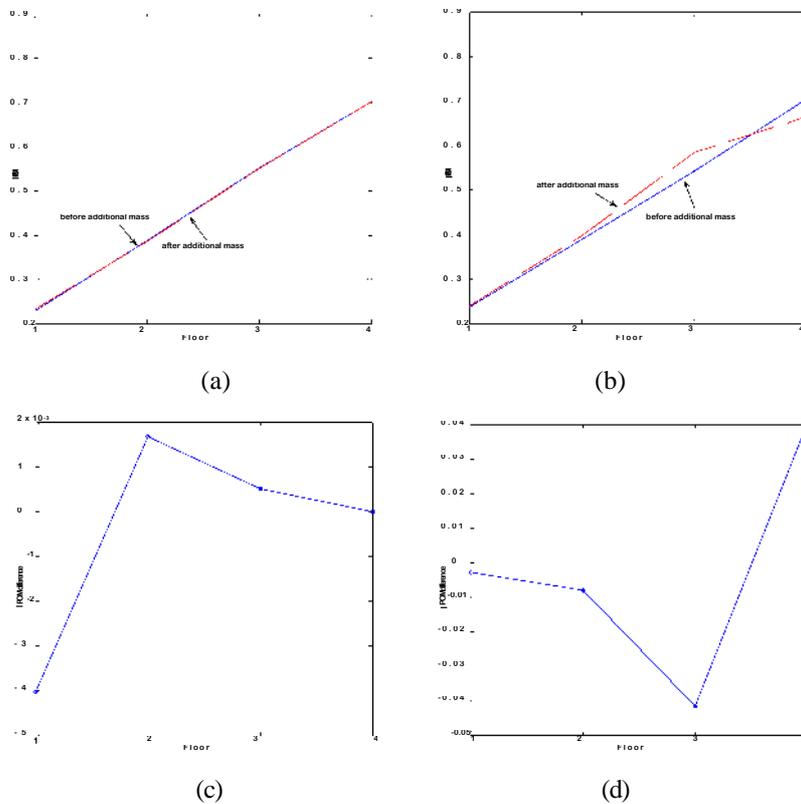


(a)
(b)
(c)
(d)

Fig. 5. POM and its difference between two states (nonuniform mass distribution): (a) POM (damage at the second floor), (b) POM (damage at the fourth floor), (c) POM difference (damage at the second floor), (d) POM difference (damage at the fourth floor)

The experimental work shows that the abrupt change of the POM due to the attachment of additional mass reflects the nature of structural damage. This experiment proved the easiness of the proposed damage detection method by mass addition without any information at the intact state.

# 4 Conclusions

This work was started from the basic idea that the dynamic response due to the attachment of additional mass should be changed. The POM corresponding to the first POV was extracted from the measured FRF response data in the neighborhood of the first resonance frequency. The POM of the damage-expected frame structure, which is regarded as the baseline datum, is compared to the other POM from an identical frame for which additional mass is attached on all floors by floor. The damage detected at the region exhibits the abrupt change in the difference between the
POMs at two states.                The validity of the proposed method was illustrated in numerical experiments and frame tests.

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