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Response features and parametric identification of shear-deformation buildings with continuous–discrete modeling

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ABSTRACT

This study presents fundamental response features of seismic shear motion in multi-story buildings with a continuous–discrete model and its degenerated ones, and shows their applications in inverse parametric identification. In particular, the building is modeled as a series of continuous shear-beams for inter-story columns/walls and discrete lumped-masses for rigid floors. Shear motion response at one location of the building is then obtainable to an impulsive motion at another location in the time and frequency domains, termed here as generalized impulse and frequency response functions (GIRF and GFRF). The GIRF and GFRF are not only fundamental in relating seismic responses at the two locations of a building structure subjected to ground seismic excitation that is not fully known due to the complicated soil–structure interaction. They also play a key role in characterizing structural responses, as well as in identifying dynamic parameters of the building.

For illustration, this study examines response features of ten-story building of Millikan Library in Pasadena, California with the Yorba Linda earthquake of September 3, 2002. With the use of the continuous–discrete model as well as its degenerated ones, structural responses are interpreted from the perspective of wave propagation, and more importantly validated with the pertinent recordings and discrete-model-based results. Parametric identification of the building with a pair of seismic recordings is then presented. This study finally comes up a conclusion that the proposed approach with continuous–discrete modeling is efficient and robust in forward predicting analysis and inverse system identification.

1. Introduction

For seismic design, vibration control, and damage diagnosis of multi-story buildings such as ten-story Millikan Library in Fig. 1, response characterization and system identification are fundamental and typically carried out with a discrete, multiple-degree-of-freedom (MDOF) model. As far as one-dimensional (1D) horizontal motion is concerned for example, the Millikan Library building can be modeled as a 10-DOF system with each floor mass and inter-story stiffness (i.e., physical parameters) calculable based on design configuration and materials. These physical parameters can also be calibrated in terms of identified vibratory features (i.e., modal frequencies and shapes—a function of physical parameters), through Fourier spectral analysis of 11-set acceleration recordings of the Yorba Linda earthquake of September 3, 2002 in Fig. 2. Subsequently, seismic demand such as structural peak acceleration to a scenario earthquake is predictable, which is useful for seismic design/retrofit and vibration control. Similarly, change of some physical parameters or high-order modal parameters are identifiable with 11-set recordings of a new earthquake, which is detection and quantification of local, minor damage in post-earthquake structural condition evaluation. Furthermore, implementing damage mechanism such as material hysteresis, plastic hinge, and/or crack into the linear 10-DOF model would make the modeling rigorous in simulating nonlinear vibratory features, thus enhancing credibility in forward predicting analysis and inverse system identification, among many other broad-based applications [1–8].

While the discrete, MDOF modeling is overwhelmingly used in structural engineering (e.g. [9,10]), it has limitation in efficiently characterizing comprehensive seismic motion in structures with *finite*-DOF modeling in general, and distorting time–space representation of seismic motion in buildings in particular. For illustration, seismic responses synthesized with the 10-DOF model will overlook the authentic floor-to-floor propagation features of high-frequency, dominant-energy waves, observed prominently in the 10–12 s time window in Fig. 2.

The wave-propagation features are even clearly exposed in floor-to-floor time shift of the first peak motion in 0–0.2 s time window in Fig. 3, which depicts pure structural acceleration responses at selected floors to an impulsive acceleration at the basement (i.e., floor 0). The pure responses in Fig. 3, referred here

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Nomenclature

A_j	cross-sectional area of the floor/wall in the jth inter-story
c_{f_j}	viscous damping coefficient of the jth floor and $c_{f_j} = \gamma_{f_j} m_{f_j}$
D_{Rr}	model-based generalized frequency response function or GFRF at response height z (or $z_R = z - z_r$) to an impulsive motion at reference height z_r
$\widetilde{D}_{j0}$	recording-based GFRF at z_j to an impulsive motion at z_0
d_{Rr}	model-based generalized impulse response function or GIRF at response height z (or $z_R = z - z_r$) to an impulsive motion at reference height z_r
F_C	viscous damping force at one floor
F_I	inertial force at one floor
F_S	shear force at the end of one inter-story
G_j	equivalent shear modulus in the jth inter-story
h	inter-story height
h_e	equivalent inter-story height of a floor
i	imaginary unit
k_j	shear stiffness of the jth inter-story and $k_j = G_j A_j / h_j$
m_{f_j}	lumped mass of the jth floor which excludes the mass overlapped with columns and walls
N	number of building story/floor
$\mathrm{sgn}(\omega)$	sign of frequency ω
r_m	mass ratio between floor and inter-story $\left(r_m = \frac{m_f}{m}\right)$
R_{Nr}	reflection coefficient between z_N and z_r, meaning down-going wave amplitude at z_r resulted from an impulsive up-going wave input at z_r which travels upward first, reflects at the free-top Nth story, and then propagates downward to z_r
T_{lm}	transmission coefficient between z_l and z_m and $T_{lm} \equiv T_{z_l z_m}$, meaning the up-going wave amplitude at z_l which is propagated upward from an impulsive up-going wave input at z_m
U_r	frequency counterpart of $u(z_r, t)$ and $U_r(\omega) \equiv U(z_r, \omega)$
U_m^d	down-going wave at z_m
U_m^u	up-going wave at z_m
$\widetilde{U}$	frequency counterpart of seismic recording
$u(z,t)$	shear displacement at height z and time t
$\hat{u}_j(t)$	shear displacement at z_j, discretized version of $u(z_j, t)$
v_j	shear wave velocity in the jth inter-story
t	time parameter in s
z^-	negative side of height z
z_R	response location z (or $z_R = z - z_r$)
z_r	referenced location
α, β	related parameters as function of ratios of inter-story impedance and cross-sectional area
δ	Dirac delta function
ε	a positive small number
ρ_j	mass density in the jth inter-story
ρv	inter-story impedance ratio
γ_j	hysteretic damping ratio in the jth inter-story
γ_e	equivalent inter-story hysteretic damping ratio of a floor
γ_{f_j}	viscous damping ratio at the jth floor
ω	frequency in rad/s
ω_j	the jth modal frequency of a modeled building
Ω_j	the jth modal frequency of a modeled building different from ones with ω_j
τ	flight time of waves (=h/v)
$\equiv$	by definition
$\lvert\tau\rvert$	absolute value of variable τ

to as generalized impulse response functions or GIRFs (to be elaborated), are extracted from recordings in Fig. 2 with the use of seismic interferometry [11] by removing influences of unknown seismic input and soil–structure interaction.

Distorting the wave features would falsely predict, likely underestimate the maximum inter-story drift, a key index of seismic demand for structural design. This is due to the fact that time-delay peak waves at two neighboring floors would have the drift calculated as difference between one peak amplitude and one non-peak value, which is typically larger than the difference between two peak values without time-delay effect. Similarly, this time-delay feature would also affect the efficacy of vibration control, if actuators installed in different floors are operated with a central feedback-control device.

More importantly, understanding and utilization of the wave features could help create an alternative wave-based approach for system identification of multi-story buildings, which is then used to improve greatly the efficiency of post-earthquake structural condition assessment. As well known, effectiveness of discrete-modeling-based system identification in general, and recognition of local physical parameters in particular, relies on a large number of recordings exemplified as 11-set recordings for the Millikan Library in Fig. 2, which is neither common nor practical for most structures currently or in the near future.

In contrast, a wave-based approach requires only a few of recordings. Take the Millikan Library again as an example. For three available recordings at the basement, 4th and 7th floors, pure structural responses or GIRFs at the 4th and 7th floors are obtainable (to be shown in Section 4), as shown in Fig. 3. Then, the 1st peak-to-peak flight time for a wave traveling from the 4th to 7th floor is measurable, which is directly related to wave velocity of the building segment. Similarly, the corresponding peak-amplitude reduction is associated with the segment damping. Both identified velocity and damping can then be related to local physical parameters such as shear modulus and hysteretic

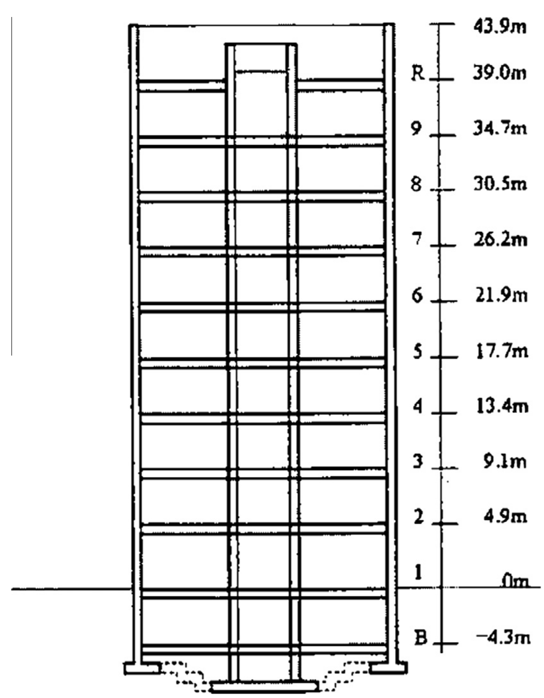

Fig. 1. Vertical cross-section of 10-story Millikan Library, Pasadena, California.